Ontario Hydro

RESEARCH DIVISION

Energy, Mines and Resources Canada | Énergie, Mines et Ressources Canada

CANMET

Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

# Semi-Automatic Welding with P-GMA for Offshore Structure Fabrication

by

T.W. Lau and R. Hopkins

Metallurgy Section
Metallurgical Research Department

Part of the Program of the Federal Panel on Energy R&D (PERD)

DSS File No.: 006SQ.23440-8-9181
DSS Contract No. 23440-8-9181/01-SQ
Scientific Authority: Dr. J.E.M. Braid

February 27, 1991

61 pp

MICROMEDIA

Canada

91602
ew 82-10

93-01532/

[redacted]

ontario hydro
research division

# Semi-Automatic Welding with P-GMA for Offshore Structure Fabrication

Report No. 90-357-P

T.W. Lau and R. Hopkins

Metallurgy Section
Metallurgical Research Department

## ABSTRACT

The potential of using the semi-automatic Pulsed Gas Metal Arc welding (P-GMAW) process for offshore fabrications was investigated through evaluations of power supplies, procedure development and welder training requirements. It was concluded that with proper precaution, P-GMAW can consistently produce defect free weldments. A typical welding procedure was developed using the Hobart ULTRA-ARC 350, but most commercial power supplies can be used with some parameter adjustments. Welder training requirements were outlined. The skills required for P-GMAW can be easily transferred to welders. However, P-GMAW requires a high level of concentration from the welder, which may not be easily taught.



| job | file | date | report no. |
|---|---|---|---|
| 81-714-600 | 823.13 | February 27, 1991 | 90-357-P |

91602
new 82-10

ontario hydro
research division

# Semi-Automatic Welding with P-GMA for Offshore Structure Fabrication

T.W. Lau and R. Hopkins

## EXECUTIVE SUMMARY

There is a clear need for a high productivity weld process which is capable of depositing weld metal of high integrity and toughness. Previous studies concentrated around mechanized pulsed gas metal arc welding (P-GMAW). This report examines the potential of semi-automatic P-GMAW, which can be directly applied to applications currently using the shielded metal arc welding (SMAW) process.

The results obtained suggested that high integrity and toughness weldments can be made using the semi-automatic P-GMAW process. The welding procedure developed, using a certain power supply, can be easily transferred to other power supplies with some modifications. The procedure developed for the two solid wires used (Kobe MGS-50LT and Nippon YM36) had a limited current value range and required special attention to the arc length. A high level of concentration from the welder was therefore necessary. A 'full weaving' technique was used in the procedure. The toughness of the weld deposits did not change significantly within the current value range and the weaving technique studied. This procedure was successfully used in an all-position pipe welding application. A flux-cored wire was also studied but showed poor deposit toughness.

A general comparison of power supplies showed that most commercial power supplies, either the constant current type or the constant voltage type, can be used for semi-automatic P-GMA welding. However, power supplies with automatic voltage control may be more difficult to manipulate. This is due to the tendency of welders to 'fight' the arc using SMAW techniques. Some power supplies studied provided a 'stiffer arc' which was better for out-of-position welding.

This report also provides a summary of P-GMAW training course requirements. Based on experience gained in this project and past Ontario Hydro experience, it is suggested that welders with prior SMAW experience can be easily taught the skills necessary to operate the semi-automatic P-GMAW process. However, the extended concentration needed, under field conditions, to deposit defect free weldments, may not be easily acquired. In Canada, there are expertise and facilities available to do the required training.

| job | file | date | report no. |
|---|---|---|---|
| 81-714-600 | 823.13 | February 27, 1991 | 90-357-P |

## TABLE OF CONTENTS


| | | | PAGE |
|---|---|---|---|
| **1.0** | **INTRODUCTION** | | 1 |
| | 1.1 | Background | 2 |
| | 1.2 | Objectives | 3 |
| **2.0** | **EXPERIMENTS AND RESULTS** | | 4 |
| | 2.1 | Welding Consumables Identification | 4 |
| | 2.2 | Welding Procedure Development | 6 |
| | 2.2.1 | Initial Trials | 7 |
| | 2.2.2 | All Position Welding Procedure | 9 |
| | 2.2.3 | Weld Metal Toughness | 10 |
| | 2.2.4 | 5G Pipe Welding Trials | 12 |
| **3.0** | **EFFECTS OF DIFFERENT POWER SUPPLIES ON THE WELDING PROCEDURE** | | 13 |
| **4.0** | **WELDER TRAINING PROGRAM REQUIREMENTS** | | 14 |
| | 4.1 | Target Groups and Core Requirements | 14 |
| | 4.2 | Sample Training Courses | 15 |
| **5.0** | **DISCUSSION** | | 16 |
| **6.0** | **CONCLUSIONS** | | 19 |
| | **ACKNOWLEDGEMENTS** | | 19 |
| | **REFERENCES** | | 21 |
| | **DISTRIBUTION** | | last page |

## LIST OF TABLES


| | | PAGE |
|---|---|---|
| Table 1 | Chemical Composition of Electrode Wires | 22 |
| Table 2 | TRA 350 Pulse Width and Base Current Setting Values | 23 |
| Table 3 | Current Value Ranges for Out-Of Position Welding Using a Hobart Ultra-Arc 350 | 24 |
| Table 4 | Average Weld Metal and Haz Charpy Toughness (Tested at -60° C) | 25 |
| Table 5 | Nitrogen and Oxygen Results | 26 |
| Table 6 | Summary of Hardness Values observed in the Deposits (UPN 2.5Kg) | 27 |
| Table 7 | Summary of P-GMA Power Source Characteristics | 28 |
| Table 8 | Summary of Groove Weldments Made | 29 |

## LIST OF FIGURES


| | | PAGE |
|---|---|---|
| Figure 1 | Charpy Impact Transition Curves | 30 |
| Figure 2 | Effect of Increasing Oxidation Potential on C-Mn-Ti-B Weld Metal Toughness Properties | 31 |
| Figure 3 | Typical Cross-Section Profile of Bead on Plate Welds Using 92Ar 8$CO_2$ Shielding Gas (5X) | 32 |
| Figure 3 | Typical Cross-Section Profile of Bead on Plate Welds Using 92Ar 8$CO_2$ Shielding Gas (5X) | 33 |
| Figure 3 | Typical Cross- Section Profile of Bead of Plate Welds Using 92Ar 8$CO_2$ Shield Gas (5X) | 34 |
| Figure 4 | Typical Cross-Section Profile of Bead on Plate Weld Using Kobe Wire, 80 Ar 10$CO_2$ Shielding Gas | 35 |
| Figure 5,a | Cross-Section of Groove Welds Using Kobe Wire, 92Ar 8$CO_2$ Shielding Gas (2.5X) | 36 |
| Figure 5,a | Cross-Section of Groove Welds Using Kobe Wire, 92Ar 8$CO_2$ Shielding Gas (5X) | 37 |
| Figure 5,b | Cross-Section of Groove Welds Using Nippon Wire, 92Ar 8$CO_2$ Shielding Gas (2.5X) | 38 |
| Figure 5,b | Cross-Section of Groove Welds Uisng Nippon Wire, 92Ar 8$CO_2$ Shielding Gas (2.5X) | 39 |
| Figure 6 | Cross-Section of Groove Welds Using Kobe Wire, 80Ar 10He 10$CO_2$ Shielding Gas (2.5X) | 40 |
| Figure 7 | Cross Section of Groove Welds Using Nippon Wire, 80Ar 10He 10$CO_2$ Shielding Gas at 160A, showing no defects (2.5X) | 41 |
| Figure 8 | Cross-Section of Groove Welds Using Hobart AVC off, 92Ar 8$CO_2$ Shielding Gas at 110A, in a vertical-Up Progression (2.5X) | 42 |

## LIST OF FIGURES


| | | PAGE |
|---|---|---|
| Figure 9 | Cross-Section of Groove Welds Using Hobart AVC on, 92Ar $8CO_2$ Shielding Gas at 110A, in a Vertical-Up Progression (2.5X) | 43 |
| Figure 10 | Cross-Section Showing bead humping at the root region when Welding at low Current (–90A) | 44 |
| Figure 11 | Typical Microstructure of Weldments made at High Current (200X) | 45 |
| Figure 12 | Typical Microstructure of Weldments made at Low Current Without Weaving (200X) | 46 |
| Figure 13 | Typical Microstructure of Weldments made at Low Current with Weaving (200X) | 47 |
| Figure 14 | Typical Microstructure of Kobe Deposits | 48 |
| Figure 15 | Typical Microstructures of Nippon Deposits | 49 |
| Figure 16 | Typical Microstructure of Flux-Cored Wire Deposits | 50 |
| Figure 17 | Longitudinal Cross-Section From an all Position Pipe Weldment | 51 |

ontario hydro
research division

## 1.0 INTRODUCTION

The construction of offshore structures for oil and gas exploration, particularly in the Arctic, has brought increased emphasis on the need for weld joints that exhibit superior low temperature fracture toughness. The proper selection of the joining process is critical to maintain this stringent requirement. At present, the most commonly used welding processes are submerged arc welding (SAW) for flat position applications, and shielded metal arc welding (SMAW) for out-of-position work. The welding cost for using the SMAW process is high due to its relatively low deposition rate and duty cycle.

Continuous wire feed welding processes such as gas metal arc welding (GMAW) and flux-cored arc welding (FCAW) have the advantage of higher deposition rate when compared to the SMAW process. Recent work on FCAW for offshore applications, however, has found that CTOD requirements (at -60 °C) are difficult to achieve /1/. This is partly due to the high oxygen level in the FCAW deposits. Future improvement in this area requires much development work in consumables (wire/flux combination).

On the other hand, considerably more promise has been seen with the pulsed-current GMAW process (P-GMAW). Substantial development work has been conducted with mechanized P-GMAW. Traditional GMAW has been limited to the short-circuiting mode in out-of-position welding, risking high susceptibility to fusion defects. Also, in the short-circuiting mode, shielding gas of higher oxygen potential has to be used. The pulsed mode allows spray transfer at a lower mean current, lowering the susceptibility to fusion defects. It also allows the use of shielding gas of low oxygen potential. The latter is important when low temperature toughness is a concern. Recent work in P-GMAW has concentrated primarily on fracture toughness evaluation using mechanized welding systems /2/.

It is recognized that the development of procedures and techniques for manual applications (semi-automatic) of the P-GMAW process will be highly desirable for offshore structure fabrication. In this form it can be implemented as a direct replacement in areas where the lower productivity SMAW process is now commonly used, without the need for investment in costly mechanized systems. However, very little work has been done to establish the viability of manually manipulated P-GMAW for offshore structure fabrication. The work reported in this document represents an organized attempt to address this issue.

## 1.1 BACKGROUND

Conventional GMAW has the advantage of higher deposition rates when compared to the SMAW process, partly due to the higher arc-on time allowable in continuous-wire processes. However, the replacement of SMAW by GMAW in the metal fabrication industry has been very slow. This has been due primarily to weld quality-related problems, such as the frequent occurrence of fusion defects usually associated with the short-circuiting transfer mode, and the inability to weld out-of-position when welding in the spray transfer mode. The later is due to the high current required (therefore high heat input) to induce the spray transfer mode, leading to an excessively large weld pool. Pulsed-current GMAW is capable of welding out-of-position in the spray transfer mode without the high heat input and large weld pool. Recent investigations have demonstrated the ability to produce mechanized high integrity welds with acceptable fracture toughness using the P-GMAW process/2,3/. These studies also looked into the metal transfer, burn-off, and fusion characteristics of a range of wire and shielding gas combinations.

Early P-GMAW systems were found to suffer from parameter set up difficulties which seriously impeded the widespread application of the process. Over the last few years, attempts to improve the P-GMAW process through power supply developments were made. 'One knob' P-GMAW power supplies that were designed with 'one drop per pulse' control logic that automatically selects optimum pulse parameters for specific wire/gas combinations were introduced. Other developments included the addition of feedback systems that modulate transient responses to arc perturbations for maintaining the welding arc in a steady state (e.g. pulse control via frequency-modulation and background current changes), and full programmability. All these were targeted to improve the arc stability and metal transfer characteristics in all position welding, minimizing the occurrence of lack of side wall fusion.

Ontario Hydro's Research Division had been conducting P-GMAW development work for the past several years. Power supplies that incorporate, variously, frequency-modulation, 'synergic control', preset programming and full programmability,have been procured during this period. Development projects have been carried out to evaluate shielding gas effects and out-of-position welding limitations, and to establish viable welding procedures for all-position carbon and stainless steel groove welds, temper-bead pressure vessel

repair, overlay welding with stainless steel, nickel- and cobalt-based alloys, and semi-automatic all position pipe welding. As a result, the P-GMAW process is now seeing significant usage in maintenance and construction of thin wall (<12.7 mm) non-nuclear components in Ontario Hydro.

Early attempts to qualify welding procedures for carbon steel pressure boundary applications revealed a serious problem with lack-of-fusion defects; this resulted in the initiation of a work program to investigate various approaches to eliminate the lack-of-fusion defects problem, with special emphasis on all-position semi-automatic pipe welding. The possible causes for these defects were systematically evaluated, and a suitable welding technique was developed for producing high integrity welds. One conclusion was that the smoothness of the prior deposited layer's surface geometry is critical for obtaining defect-free welds. Consequently, a full weave technique has to be employed for all position welding, especially when the vertical-up progression is involved. Another critical observation was that appropriate welder training is proving to be one of the most important requirements for obtaining high quality welds. This program was completed in 1987 with the successful qualification on an all-position carbon steel pipe welding procedure/4/.

The current project provided an opportunity to review past Ontario Hydro experience and to develop the necessary know how in order to transfer the technology to applications in offshore construction and maintenance. Thus, part of this project reviewed the practical requirements for transferring existing technology. The following aspects, relevant to offshore fabrications, were addressed in a practical manner.

Offshore weldments require high toughness at low temperatures. To achieve the required toughness, filler materials for offshore applications usually contain significant amounts of alloying elements (Ti, B, Ni, Mn, Si etc.). Thus the welding characteristics of these filler wires will be different than carbon-manganese filler wires. The necessary welding parameter adjustments, if any, were studied. Offshore structure fabrication requires frequent welding of thick cross sections (>38 mm). The behaviour of the welding arc in narrow grooves, and the required skills to manipulate the arc were investigated in this project. The influence of factors such as average welder skill, field welding conditions, and the type of power supply available, on welding procedure were considered. The modifications necessary to accommodate changes in the above factors were discussed.

## 1.2 OBJECTIVES

The main goal of the project was to evaluate whether semi-automatic GMAW could produce welds with low incidence of defects in simulated offshore applications. This goal was achieved through the realisation of the following objectives.

1) To identify, through literature, three welding wire/shielding gas combinations that give deposits which meet the low temperature toughness requirements for offshore structure fabrication.

2) To establish pulsed-current welding parameters (Pulse peak current, background current, pulse time) for the three selected wire/gas combinations to obtain optimum droplet transfer using a programmable, frequency-modulated P-GMAW power supply.

3) To develop all-position, semi-automatic (manually manipulated) welding techniques that will produce welds with a low incidence of fusion defects.

4) To evaluate the performance of several commercial P-GMAW power supplies for offshore fabrication applications, and to assess the transferability of welding procedures established for one power supply to another.

5) To identify an appropriate approach for training offshore industry field welders in these newly established welding techniques.

This report, documents the results and achievements obtained in addressing the objectives.

## 2.0 EXPERIMENTS AND RESULTS

There were four major tasks in this study:

1) Welding consumables identification
2) Welding procedure development
3) Welding power supply evaluations, and
4) Welder training program requirement identification.

The work done in these tasks and the results obtained are listed in detail below.

### 2.1 WELDING CONSUMABLES IDENTIFICATION

Weldments in offshore structures operating in the Canadian Arctic and the east coast need to meet toughness requirements at -50 °C. This critical temperature is lower than that of the North Sea requirements (-20 °C). Thus, in identifying consumables to be used, Canadian studies were emphasised.

Dorling et al /2/ studied P-GMAW of thick-section steels for low temperature applications. Several filler wires were studied. Bearing in mind that the shielding gas has significant effects on the properties of the weld bead, it was shown that a C-Mn-Si-Ti wire (Thyssen K-NOVA) and a C-Mn-Ti-B wire (Kobe MGS-50LT) had good charpy and CTOD values. Figure 1 shows the Charpy transition curves obtained by Dorling et al. The Kobe wire deposits were shown to have higher Charpy and CTOD values than the Thyssen wire deposits except in the case when hydrogen additions were made to the shielding gas. In general, CTOD values at -45°C were less than 0.1 mm. The Thyssen wire deposits produced microstructures consisting of very fine acicular ferrite, with small amounts of grain-boundary ferrite and ferrite with aligned second phase. The microstructure of the as deposited Kobe MGS-50LT deposits was entirely composed of acicular ferrite.

Chiu and Malik /3/ studied GMA consumables for offshore and petrochemical applications. Their results showed that the Nippon YM-36 wire had similar CTOD values at -30°C and -50°C as the Kobe MGS-50LT wire. The Nippon wire had a higher alloy content and therefore a higher hardenability, hence it was anticipated that toughness would be better retained at higher heat inputs.

Due to the high toughness shown by the Thyssen, Nippon and Kobe wires, and because of the availability of mechanized welding data of these wires, they were chosen for studies in this project. The Kobe and Nippon wires were only available at a minimum diameter of 1.2 mm, so that this was the diameter of the three wires studied. The composition of the wires are shown in Table 1. Part way through the project, a decision was made to replace the Thyssen wire with the Nippon SF-36E wire. The latter was then a newly available flux-cored wire. It was well recognized that flux-cored wires lack the toughness properties at low temperatures /1/. However, the flux-cored process is attractive because of the superior deposit bead profile, which lowers the frequency of fusion defect occurrence. This makes the flux-cored process a much more forgiving process compared to GMAW. It was felt that a study of the SF-36E wire should be made to find out whether the newer generation flux-cored wires could provide better low temperature toughness.

The shielding gas has significant effects on the low temperature toughness of the weld deposits. Chiu and Malik /3/ selected C5 gas (95%A-5%$CO_2$) for their detail studies based on the results of the oxygen analysis and microstructure evaluation, and the perceived better operating characteristics observed in their preliminary studies. Thomson et al /5/ studied the influence of argon based shielding gas composition on P-GMAW of offshore materials and arctic pipelines. Figure 2 shows their results on the effects of $CO_2$ content on the Charpy and CTOD values of the Kobe MGS-50LT deposits. Figure 2 shows that optimum CTOD and Charpy results were obtained when the $CO_2$ content of the shielding was between 8% to 12%. Thomson et al also showed that addition of He to Ar-$CO_2$ improved interpass fusion and side wall fusion for welding of thick section plates in the vertical-up progression. With an 80Ar-10He-10$CO_2$ shielding gas, interpass

fusion was improved by 112% and side wall fusion was improved by 60% when compared to the Ar-10%$CO_2$ shielding gas. The experience in Ontario Hydro showed that small changes in shielding gas has little effects on the welding characteristics of a given wire. Shielding gas may affect significantly the low temperature toughness values, but since applications at Ontario Hydro seldom require low temperature properties, there were no systematic studies in this aspect.

A shielding gas composition of 92% Ar and 8% $CO_2$ was selected for most of the works done in this project, based on the above information and the fact that the Kobe MGS-50LT and Nippon YM-36 wires had similar compositions. The lower $CO_2$ limit was selected to minimize the oxygen content in the weld deposits, which should raise the upper shelf energy absorption of the weld metals. Also it was reported by Thomson et al that higher oxygen potential in the shielding gas might lead to increased incidence of weld metal lack-of-fusion defects. An Ar-10%$CO_2$-10%He gas was also tried. The difficulties in obtaining the proper gas mixture led to the decision to delete this gas.

## 2.2 WELDING PROCEDURE DEVELOPMENT

To develop an all-position welding procedure for the selected wires, metal transfer characteristics were examined in an initial set of bead on plate tests using pulse parameters previously established for carbon steel welding, with adjustments to accommodate the new gas and wire combinations. Groove welds were then made in different welding positions (horizontal, vertical-up, 45° overhead, and overhead) to establish the current range and other parameter range for the different welding positions. The proper weaving techniques were also established. A leading torch angle of 15° to the vertical and a preheat of 177°C (350°F) was used through out this project. The established parameters were then used on 5G pipe welding trials. Since the heat inputs and weaving technique used in the different welding positions would be different, it was necessary to establish that the weld metal toughness was not adversely affected by the changes in the welding parameters. Hence, charpy tests were done on a set of test coupons made using different heat input and weaving techniques.

A successful welding procedure reflects proper incorporation of power supply capabilities (including current and voltage settings), consumables properties and welder skills. It is obvious that the possible number of combinations of the three facets are very high. In this project the consumables were already selected. The approach was to use a power supply to establish the nominal parameters and then to note the changes necessary if a different power supply were to be used. The required welder skills, specific to offshore applications, were also summarized and commented upon.

### 2.2.1 INITIAL TRIALS

The initial trials used the programmable OTC TRA350 machine. This is a fully programmable self-regulating power supply where parameters such as peak and background current levels ($I_p$ and $I_b$) and peak pulse time ($T_p$) can be independently set. Thus, with appropriate parameter selection, the ability to accommodate different welding wire/shielding gas combinations is nearly unlimited. Recommended programs for the more common wire and gas combinations are given in the OTC manual. Table 2 listed the pulse width and background current values corresponding to the settings available in the TRA350 machine. In addition, a reference voltage which corresponds to arc length is set, and if the arc length changes during welding, the power supply will adjust the wire burnoff rate automatically by varying the background or low pulse duration, thus restoring the preset voltage; this method of arc length control is termed 'frequency-modulated' control. The TRA 350 also has features such as hot start (a high current can be applied during arc initiation to avoid defect formation), crater-fill, pre- and post-purge gas flow, and wire conditioning, which avoids the formation of an excessively large ball at the end of the wire tip during arc extinction.

The standard carbon steel programs, designed to be used with Ar based shielding gases containing 10 to 20% $CO_2$ (E pulse, B background), were able to provide a stable arc when used for the bead-on-plate tests with the 92Ar-8$CO_2$ gas. The bead-on-plate tests aimed to study the general bead shape, and particularly the wetting angle. A mechanized system was used to lay beads in the flat position at a travel speed of 6.8 mm/s (16 imp), using average current settings of 100A, 150A, and 170A, with all three wires. Minor spattering was experienced when welding at 100A, otherwise, smooth transfer was observed. When a 0.9mm Thyssen wire was tried, smooth transfer was observed over the entire current range. Cross-sections of the beads showed good wetting angles, with the typical 'finger type' penetration usually associated with high argon content spray welding. Figure 3 shows the cross-sections obtained.

Bead-on-plate welds were also made using the 80Ar-10He-10$CO_2$ shielding gas and the TRA350 power supply, at the recommended carbon steel settings of (E) pulse, and (B) background. The average current used was about 120A. Figure 4 shows that the wetting angles of the beads improved compared to the 92Ar-8$CO_2$ shielding gas, and the crowns of the beads were more triangular in shape. The penetration was about the same as when 92Ar-8$CO_2$ shielding gas was used.

Manual groove weld tests were then conducted using 25 mm thick LT60 plates with the TRA 350 power supply. The joint configuration had an 60° included angle with a 4.7 mm wide root gap and a backing plate. Both the Nippon and Kobe wires were tested using 92Ar-8$CO_2$ gas at a current range of 100-120A, and a travel speed of about 5.1 mm/s (12 ipm). Some minor modification to the factory recommended procedure for 1.2 mm carbon steel wire was found to be necessary for optimum transfer characteristics ($T_p$=F, $I_b$=B).

The same set of parameters was applicable to both the Nippon and the Kobe wires. Two weave techniques, a 'full weave' and a 'split weave' (16 mm maximum weave) patterns, were used in the vertical-up welding position. In the horizontal welding position, the 'stringer' technique was used. A total of six groove welds were made using the Ar-$CO_2$ gas.

In the vertical up welding position, it was observed that excessive spattering was encountered when filling the bottom region of the groove. Increasing the background current seemed to improve the transfer, but did not eliminate the problem. The spatter problem could be caused by the excessive contact tip to work distance due to the large cup size of the OTC torch which prevented the gun from reaching the bottom of the groove. When using the full weave technique, frequent stops between passes were necessary due to the high heat input, to keep the interpass temperature below 180°C (350°F). However, such overheating problem is not expected when full size components are involved. An average current of 110A was used for all welding done in the vertical-up progression.

An average current value of 120A was used for welding groove test coupons in the horizontal position. The usual problem of weld deposit 'sagging' was encountered, a condition which was found to be very conducive to the formation of fusion defects. It was apparent that a small 'weave' technique at critical areas, a method developed in a previous program to prevent defects, must be applied to this application. When sectioned, all the six weldments showed numerous lack-of-fusion defects, as shown in Figure 5.

The 90Ar-10He-10$CO_2$ shielding gas was then studied, and the same power supply settings were found to be applicable. Two groove welds were made in the horizontal welding position at an average current of 120A using the Nippon wire. This gas gave deeper bead penetration and better wetting at the toe of the bead. There was no obvious sagging of the bead. When sectioned, the fusion defects found were smaller in size and less numerous (Figure 6). It was also observed that the correct placement of the beads was more critical when using this gas, as evidenced by the large defect shown in Figure 6b which was resulted from deliberately misplacing a bead. An additional horizontal groove weld was made with a high average current value of 160A to see the effects of power density. The nominal heat input was maintained at roughly the same value as the lower current weldments by a faster travel speed (6.8 mm/s v.s. 5.1 mm/s). The faster travel speed was also necessary to avoid roll over of the deposit. The resulting weldment, as shown in Figure 7, contained no fusion defects.

The above results suggested that the TRA 350 power supply could produce defect free weldments at higher current settings. This implied that out-of-position welding would be a problem. The use of Ar-He-$CO_2$ gas reduced the size and frequency of the defects, but did not eliminate the problem. The failure to produce sound welds was at the time

attributed to the limitations of the power supply. Hence another power supply was used to do further procedure development works. In retrospect, this decision represented an oversimplification of the problem. This aspect will be discussed in the power supply comparison section.

### 2.2.2 ALL POSITION WELDING PROCEDURE

The Hobart Ultra-Arc 350 power supply was used for the all position welding procedure development works. This power supply is a constant-current primary inverter DC type machine that provides ten factory-programmed weld schedules for certain wire sizes. The wire feed speed is used to modulate the arc length variations. All the pulse parameters float when the burnoff rate (wire feed speed) changes, thus maintaining a stable arc, yet retaining the one drop per pulse characteristics. The machine also provides automatic arc length (arc voltage) control (AVC). This AVC feature compensates for fluctuations in the torch/gun-to-workpiece distance, and maintains a constant arc voltage. With the AVC control off, the power supply behaves similar to a manual shielded metal arc welding machine. The average current output is controlled by a single knob.

The factory program Schedule 2. for 0.045 mild steel wire was used for the high toughness wires, with the 92Ar-8$CO_2$ gas. A lead angle of 15° to the vertical was again used for all the welding done. A stable arc and acceptable transfer characteristics were observed at an average current setting as low as 90A. Both the Kobe and Nippon wires were tried, with the AVC control of the machine in both the on and off position. Sound groove weldments in the horizontal and the vertical-up welding positions were made with the AVC control off. The dimensions of the groove preparation were the same as those in listed in the last section. Figure 8 shows an example of the cross-section of these welds. In both the horizontal and the vertical-up welding positions the maximum current allowable, without bead sagging or rolling, was 130A. In the vertical-up welding position, a full weave technique was used. With the AVC on, defects were observed, as shown in Figure 9. However, the size and occurrence frequency of the defects were much smaller than those observed when the OTC TRA 350 power supply was used. There was no simple explanation for this observation. The welder has extensive experience with P-GMAW and has a good understanding of the functions of the AVC. It was simply concluded that semi-automatic P-GMA welding should be done with the AVC at an off position. Further work with the Hobart Ultra-Arc machine was done with the AVC in the off position.

In the 45°-overhead welding position, the maximum allowable current was found to be 100A. In the overhead welding position, the maximum allowable current without weld pool sagging was found to be 95A. Thus the operational current range in the overhead welding position was extremely narrow. At these low current values, there were difficulties when laying weld beads at the bottom region of the groove. The arc seemed to lack the stiffness to go to the side of the groove, and as a result the weld bead showed

a hump at the centre (see Figure 10). When an S6 wire was tried, using the same groove preparation and welding parameters, this 'humping' was not observed. It seemed that the S6 wire has better wetting properties at this low current value. On the other hand, when the high toughness wires were tried on a wider groove preparation, the 'humping' effect also disappeared. The filling passes of the vertical-up and 45° overhead weldments were made using a 'full weave' technique.

The Nippon SF-36E flux-cored wire was then studied. In trials using groove preparations, it was quickly established that a minimum average current value of 160A was necessary to induce spray transfer with the wire. In the flat position, average current settings in excess of 200A had been tried without obvious difficulties. In the vertical-up and overhead welding positions, the weld pool could be held with average current setting as high as 160A. Obviously, the presence of a flux allowed the use of a higher current value. Slag detachment was relatively difficult, but it was observed that slag removal was only necessary after three or more passes.

Table 3 summarizes the average current ranges usable for the solid wires and the flux core-wire. Using the Hobart Schedule 2 program and the proper average welding current range and weaving techniques corresponding to the welding positions, defect free groove weldments were successfully made. These average current values and weaving techniques were then applied to 5G pipe welding trials. However, before this was done, it was necessary to establish that the average current variations did not have significant effects on the toughness values of the weld deposits.

### 2.2.3 WELD METAL TOUGHNESS

The chemistries of the wires used were designed to provide high toughness at low temperature. However, the welding procedure will influence the end results. Groove welds were made in the flat welding position, varying independently the average current value and the weaving technique. With similar travel speeds, a change in the average current value will change the heat input and therefore the cooling rate of the weldment. A high average current value of 160A and a low average current value of 110A were used for the solid wires (Kobe MGS-50LT and Nippon YM-36), to see the effects of heat input on toughness, using stringer bead techniques. A high average current of 200A and a low average current of 160A were used for the Nippon SF-36E flux-cored wire. At the lower average current values, coupons were also made with a 'full weave' technique. Weaving could provide less protection of the weld pool from the shielding gas. This might, among other things, change the Ti content of the weld deposits which had been shown to have an effect on the weld metal toughness /6/. The changes in toughness, if any, due to different weaving techniques, are of great interest. The weaving would also increase the effective heat input of the weldment. Altogether, a total of 9 coupons were prepared.

Three weld metal and three HAZ charpy samples were prepared from each coupon. All the samples were machined out at about mid-depth of the coupons. The charpy tests were performed at -60°C, and Table 4 presents the results obtained. There was a large scatter in the toughness of the HAZ, associated with the exact location of the notch in the HAZ. For both solid wires, there was a slight decrease in toughness when the heat input was increased or when weaving was used. The Nippon solid wire seemed to show better toughness in all cases and the changes due to heat input or weaving techniques were less. However, both solid wires showed excellent toughness at the welding conditions studied. The flux-cored wire, on the other hand showed unacceptable toughness values. Because of the low toughness observed, the study of the flux-cored wire was discontinued.

To understand the changes in toughness, nitrogen and oxygen analysis, as well as the microstructure of the weldments were examined. Table 5 shows the nitrogen and oxygen results. The oxygen variations in the Kobe wire deposits resulting from heat input or weaving technique variations were small. The nitrogen content increased with lower current value and the use of weaving. The Nippon solid wire deposits showed a similar trend in the nitrogen content as the Kobe wire. However, there was a marked increase in the oxygen value with the lower heat input. The nitrogen and oxygen contents of the flux-cored wire showed similar trends to that of the Nippon solid wire. The oxygen contents of all the weldments were within the range of 250 to 400 ppm, which is the optimum range for toughness as suggested in literatures /7,8/. Based on the oxygen results, the low toughness values of the flux-cored samples cannot be explained.

The microstructure of weldments are shown in Figures 11 through 13. A mixture of acicular ferrite, fine grain boundary ferrite and ferrite with aligned second phase were observed in all the weldments. Although the oxygen contents of the comparable welds were similar, the average inclusion diameter observed in the flux-cored deposits seemed to be larger. At higher magnifications (see Figure 14), it was shown that the Kobe deposits contained mainly acicular ferrite type structures with the largest aspect ratio when compared to the deposits made with the other two wires. The ferrite grains in the Nippon deposits were more equiaxed in nature with occasional precipitates within the grains as shown in Figure 15. The flux-cored deposits contained mainly very fine acicular ferrite but with patches of coarse structures. The areas marked A in Figures 11c and 13c are examples of these coarse structure patches. Figure 16 shows the acicular ferrite and coarse structures at 1000x magnification. There were more second phase particles among the acicular ferrites comparing to the other two deposits. The high current used with the flux-cored wire when making the filler passes created coarse-grained patches in the weld metal zone. This was due to the higher heat input and subsequently a larger coarse-grained zone associated with the weld bead. The lower toughness of the flux-cored deposits may be partly due to these coarse-grained patches.

The hardness values of the deposits (VPN 2.5 kg) are shown in Table 6. The flux-cored deposits shows higher hardness values, mainly due to the finer microstructures. The higher hardness probably also contributed to the lower toughness of the flux-cored deposits.

### 2.2.4 5G PIPE WELDING TRIALS

A 20mm thick with 203mm outer diameter pipe was used for 5G (fixed pipe, axis horizontal) welding trials. The V-groove preparation had a 60° inclusive angle and a gap width of 4.7mm with backing. Two welders were asked to make one weldment each. In each case, the double up weave technique was used. Half of the pipe was filled with the Nippon solid wire and the other half with the NS 70-S6 wire. This was done to have a detail comparison of the welding characteristics of the S6 and the high toughness wire. There were great difficulties in depositing a root pass with the high toughness wire due to the 'humping' effect as described earlier. Therefore, Gas Tungsten Arc (GTA) welding was used to deposit the initial two passes in the pipe, which was subsequently filled by P-GMA welding using a 'full weave' technique. Except at the root regions, the welding characteristics of the S6 and Nippon wires were found to be similar. The two weldments were sent out for X-ray radiography.

The pipe weldment produced by one of the welders showed strong indications of fusion defects while the other pipe weldment passed the inspection. Subsequent cross-sectioning of the pipe weldments confirmed these results. In the defective pipe weldment, there was higher frequency of defects at the six to three o'clock position in both the S6 and high toughness weld metal zones. This suggested the main cause of the defects was operator technique. A comparison of the welding techniques of the two welders was then made. Both welders used the current range outline in Table 3 and a full weave technique to fill up the weldment. Proper grinding and cleaning was also followed when stoppage was necessary. The only significant difference was that the welder who produced the defective weldment was over conscious about spatter and had the tendency to pull the torch back. Thus the arc length used might be longer. This welder was then asked to repeat the pipe welding trial, with the instruction to use a 'shorter' arc length than before. The resulted weldment showed no significant fusion defect indications when examined with X-ray radiography. This pipe weldment was then sectioned. The longitudinal cross-section showed no fusion defects (Figure 17).

The pipe welding trials confirmed that in a narrow gap, low current welding using the high toughness wire would be a problem. Subsequent trials with other power supplies in groove welds showed similar problems. This might be a result of the chemistry effects of the wire (which affect the surface wetting angle of the weld pool) or the energy density of the electric arc. It was also shown that the problem may be overcome by using a higher current values or a wider gap. Since it is not practical to use higher current value at out-of-position welding, a wider gap is the only practical solution. When using a wider

gap, the joint preparation may be modified to minimize the amount of weld metal necessary to fill the groove. A U-joint preparation, for example, may be used.

In summary, the pipe welding trials showed that all position defect free weldments can be obtained using the semi-automatic P-GMAW process. However, the range of current usable was limited, and special attention must be paid to maintain a short arc at the root region of a groove. The later requires extensive and continuous attention from the welder. Under field conditions, extended attention from the welder may be difficult.

## 3.0 EFFECTS OF DIFFERENT POWER SUPPLIES ON THE WELDING PROCEDURE

The limited tests made in this project could not provide a fair comparison of the performance of the power supplies studied, and there was no clear criterion to compare the performance of power supplies. The information gathered in this project was intended only to provide a guideline on changes in parameters that might be necessary when changing from one power supply to another. The power supplies studied in this project included the TRA 350, the Hobart ULTRA-ARC 350, the AIRCO PULSARC 500, and the Fronius TPS 500. Table 7 summarizes the major characteristics of the power supplies studied. The TRA 350 and the Hobart ULTRA-ARC 350, which are similar machines, were briefly described in previous sections. The major difference between the TRA and Hobart machines is as follows. The TRA 350 changes the pulse current frequency and the background current value (therefore the average current value) to maintain a constant arc length, while the Hobart machine changes the wire feed rate (the pulse frequency and the background remain constant) to maintain a constant arc length.

The AIRCO PULSARC 500 is a conventional constant voltage machine, which can be employed in both the pulsed-current mode and the non-pulsed-current mode. There is no automatic current or voltage control mechanism. When operating in the pulsed-current mode, the average current value is changed by changing the frequency of the current pulsation, while the background current value is maintained at a relatively high constant level (100A). The time required to reach the peak current value during pulsation is longer than most other power supplies, resulting in the 'soft' arc observed by some welders. The noise produced by the power supply at the pulsation frequency is annoying to some welders. Main advantages of this machine are its well known durability and low cost.

The Fronius TPS 500 is a complicated machine. It has both constant current and constant voltage characteristics. During operation it continuously switches back and forth from CV mode (during current pulsation) to the CC mode (during background current period). It is fully programmable such that all parameters ($I_p$, $I_b$, $t_p$, pulse frequency and wire feed rate) can be independently set at any given average current value. Compared to other power supplies studied, this machine provides the stiffest arc and hence may be better suited for all-position applications. This power supply is also able to tolerate large

variations of arc length, and it is not clear whether a voltage feed back mechanism is used to control the arc length. One disadvantage of this power supply is its high cost, almost twice as expensive as some other power supplies. The lack of technical support in North America is also a concern to many welding facilities.

To evaluate the different power supplies, one welder was asked to make groove welds in the vertical-up and the 45° overhead welding positions, using the four power supplies. The shielding gas used was 92Ar-8$CO_2$. Table 8 presents the results obtained. It must be emphasised that if another welder were performing the welding, the results obtained might be different. The experience and preference of a welder plays a significant role in the quality of the weldment, as in any welding processes. Table 8 shows that defect free welds were obtained with the Fronius, Airco and the Hobart (AVC off) machines. When using the TRA and the Hobart (AVC on) machines, fusion defects were observed in the weldments. Obviously with sufficiently high current values, any power supply can produce defect free weldments. However, the resulting weld pool size limited the usable welding current values. Among the power supplies studied, the Hobart machine had the largest current range, as indicated by machine meter readings, within which a stable arc can be maintained. Beside welder skill, certain features of power supplies can influence the quality of the welds. This will be covered in the discussion section.

## 4.0 WELDER TRAINING PROGRAM REQUIREMENTS

The information available from this project suggested that the semi-automatic P-GMAW process could be used in offshore applications. The transfer of this technology requires proper training of the welders. The training program requirements are outlined in this section.

### 4.1 TARGET GROUPS AND CORE REQUIREMENTS

The training program should at least aim at two groups of people; the engineers and senior technicians who have the responsibility to develop welding procedures for specific applications, and the welders who carry out the day to day welding activities. It is assumed that most of the people in the two groups have experience in the SMAW process. Obviously, the training provided to the engineer and senior technician group should put emphasis on the theoretical aspects of the welding process as to provide necessary information on proper procedure development. On the other hand, the welder training program should emphasize hands on experience. The following are essentials that should be included in the program.

a) GMAW basics: The basic differences between a continuous wire process and that of the stick process should be discussed. Thus the proper arc shielding with the gas should be emphasised. The effects of shielding gas and current on weld bead

profile and penetration should be explained. The difference between conventional GMAW and P-GMAW should be covered.

b) Metal transfer: The different metal transfer modes possible in GMAW should be covered. The concept of transition current and the concept of current pulsation should be explained. For the welders, recognition of different transfer modes, by monitoring the arc and by sound should be explained.

c) Welding parameters: Welding variables such as wire feed speed, voltage, polarity, and stick-out, which are not commonly monitored in the SMAW process, should be identified and their effects on the welding operation should be explained. Other welding parameters should also be covered (gun angle, welding speed,wire diameter etc.). For the engineers, the limitation of these variables on welding procedure development should be reviewed.

d) Welding techniques: The typical fusion profile of a GMAW bead and the reasons why GMAW is prone to fusion defects should be explained. Techniques to avoid these defects, such bead positioning (in stringer bead technique) and proper weaving techniques should be demonstrated. Practical techniques to perform off-position welding should be covered and practised by the welders. As demonstrated in this project, the importance of maintaining a short arc length in out-of-position groove welding must be emphasized.

e) Power Supplies: Welders should be exposed to different power supplies. The power supplies studied may include CC and CV types, programmable and non programmable types, and those with and without AVC control. For the engineers, the different current pulsation control logic of power supplies and their implications on welding operation (such as 'arc stiffness') can be included. Simple trouble shooting guidelines is also desirable.

## 4.2 SAMPLE TRAINING COURSES

Ontario Hydro has developed courses for training its internal welders. These training programs emphasis practical skills and aim to qualify the welder as per MCCR requirements. An outline of the GMAW and P-GMAW program is shown in Appendix A. In the course of this project, two field welders, while being trained for the P-GMAW process, were asked to make coupons using the high toughness wires. These field welders had no prior experience with the GMAW process. Coupons in the flat and vertical-up welding positions were made by these welders using both the Airco and the Hobart machines. Sectioning of these coupons showed that they were defect free. Thus, with proper instructions, acquirement of GMAW techniques by welders can be readily achieved.

The Welding Institute of Canada (WIC) offer training programs to its member and other public companies. Basic instruction materials exist in modular form, and these materials can be tailored for specific requirements. Appendix B shows the outline of a course WIC provided for a certain company. In this particular course, both theory and practical skills were emphasised.

The above two examples can be used as the basis for the development of training courses for specific situations. Obviously, a successful course must account for the specific needs of the group, which may not at first be easily identified.

## 5.0 DISCUSSION

It is well known that P-GMAW is prone to fusion defects. This is related to the bead fusion profile resulting from the heat distribution in the arc and the metal flow in the weld pool. In the flat welding position, fusion defects can be avoided by using sufficiently high welding current. However, this is not practical in out-of-position welding. Studies on the effects of consumables (mainly shielding gas) and power supplies for the mechanized process suggested that the problem can be minimized. This project examined whether defect free weldments can be made with high confidence using the semi-automatic process. The results suggested that if proper cautions are taken, the process can be used with confidence to weld offshore materials. A welding procedure using the Hobart Ultra-Arc 350 power supply was developed in this project. This procedure should be easily modified for other power supplies. It was also shown that the welding characteristics of the offshore filler wires were similar to that of the S6 grade wires. However, extra precaution was required for low current, narrow groove situations. Since the project was done under laboratory conditions, where proper control of all parameters were possible, further trials under field conditions may be necessary before a final recommendation is made.

To ensure success in applying the P-GMAW process to offshore fabrication, three aspects of the welding technology must be carefully managed. These are the availability of consumables and hardware, existence of proven welding procedure and the availability of properly trained welders. Although there are limitations in all the three aspects, they can be easily developed.

When welding in a groove at low average current, the high toughness wire deposits formed a 'hump' at the centre. This increased the chance of fusion defect formation at the root region when subsequent weld beads were laid. This 'humping' might be related to the wetting characteristics of the weld pool and may be related to the alloy contents of the high toughness wires. The two wires studied contained alloying elements such as Ti and B which are strong deoxidizers. Thus the oxygen contents of the weld pools may be lower than a carbon wire weld pool, resulting in different surface tension characteristics of the weld pool. The selection of a high toughness wire which offers better wetting

characteristics at low welding current could lower the chance of fusion defect formation at the root region. Another way to reduce the chance of fusion defect occurrence is to modify the joint preparation by using a wider gap width or a completely different joint design (e.g. a U joint). The two high toughness solid wires studied were able to tolerate the changes in welding current and weaving techniques used in developing the welding procedure, giving only minor changes in deposit toughness.

If a flux is added to the weld pool, the bead profile will be changed completely, and the possibility of fusion defects will be drastically reduced. This concept is partly responsible for the development of flux-cored wires. Unfortunately, low temperature toughness values of flux-cored deposits are poor, as confirmed in this study. Compared to the solid wires studied, the toughness of the flux-cored wire was an order of magnitude lower at -60°C. A combination of factors, such as the patches of coarse-grained observed, the higher hardness values and the larger average inclusion size, may contribute towards the low toughness, but probably is not sufficient to explain the difference in toughness seen. High resolution metallography, such as Transmission Electron Microscopy, may provide further explanation. In the literature, low flux-cored deposit toughness was mainly attributed to slag entrapment between passes.

Further development of consumables, both in terms of solid wire composition and flux/wire combination, respectively for better wetting properties and better toughness, will certainly promote the applications of P-GMAW.

Some power supplies are equipped with automatic voltage control (AVC) mechanisms. In the case of the Hobart Ultra-ARC 350, a switch allows the AVC to be turned on or off. AVC may not be a desirable feature in semi-automatic welding. Even with the present welder. who has extensive experience with the P-GMAW process, it was observed that defects were found in weldments made with the TRA machine and the Hobart machine with AVC control turned on. On the other hand, using the Airco machine, which is not equipped with AVC, and the Hobart with AVC turned off, sound welds were made. It is expected that welders with less experience in P-GMAW will have more difficulties with machines equipped with AVC. It is common in SMAW to manipulate the arc length to control the weld pool and to obtain proper fusion. If the same techniques were applied to P-GMAW using a power supply equipped with AVC, the welder will be 'fighting' the arc, leading to increased likelihood of fusion defects. Other experience in Ontario Hydro confirms the preference of P-GMAW without AVC.

The control and pulse logic of a power supply significantly influence the stiffness of the arc. While it is not possible to quantify 'arc stiffness', the behaviour of the arc at low welding current may give a guideline. In this sense, both the Hobart and the Fronius provided stiffer arcs than the other power supplies. In other Ontario Hydro studies, the Hobart power supply was observed to provide good arc stability at low average welding current values. The Fronius power supply has been described as providing the 'stiffest

arc'. Arc stiffness is an important characteristic in out-of-position welding or when welding in narrow grooves. The experience with the Airco machine in this project suggested that a 'soft' arc alone did not prevent successful welding.

There was no preference on welding with CV or CC machines. Both CV machine (Airco) and CC machine (Hobart) were able to give defect free weldments. However, with electronic controls, the newer power supplies do not behave as pure CC or CV machines in the conventional sense. Fully programmable machines offer flexibility in the development of welding procedures. However, it was found that factory pre-programs were able to be used with the high toughness wires studied in this project. While full programmability is a positive feature, it is felt that it is not an essential feature in offshore applications.

Defect free weldments were made successfully with at least three power supplies (Hobart, Fronius and Airco). In each case, pre-programs or parameters suggested for carbon steel wires were used. From this information, it is felt that with proper precaution, any power supply can be employed to make sound weldments on offshore materials. The TRA power supply used in this project was an older generation machine when compared to other power supplies. The new generation OTC products probably offer more flexibility. A welding procedure lays out the current and the voltage settings to be used, as well as the weaving techniques and bead deposition sequence. The current and voltage settings usually refer to the meter readings or the dial settings and, in most cases, do not reflect the actual voltage or current values across the electric arc. In other words, the energy efficiency of each power supply is different. Thus the voltage and current values established for the Hobart power supply in project will need adjustments when another power supply is substituted. The parameters established in this project can be used as the starting parameters for any power supply, but tuning of the voltage and current by a few percentage will be necessary. This probably reflects the need to compensate the different energy efficiency for each power supply, rather a change of actual voltage or current values. For example, this study suggested a higher machine current setting can be used for the Hobart power supply than the TRA power supply, but this does not mean that at the different settings, the actual voltage and current values across the arcs are not the same.

When welding with the stringer bead technique, proper positioning of the beads is critical in minimizing the occurrence of fusion defects. However, this criteria is relaxed with using a weaving technique. The results in this project showed that weaving did not significantly decrease the toughness of the deposits. Ontario Hydro has a successful record transferring the P-GMAW techniques to welders who have prior experience in SMAW. The training program requirements listed in this report are partly based on past Ontario Hydro experience. Within Canada there are expertise and facilities available such that welders can be quickly trained to operate the P-GMAW process. While the basic skills

can be easily transferred, the high level of concentration demanded from the welder during welding can be difficult to instill.

## 6.0 CONCLUSIONS

The following conclusions can be drawn from this study:

1) Provided proper caution is taken, the semi-automatic P-GMAW process can be used to weld off shore materials.

2) The high toughness wires studied in this project provided good weld metal toughness at -60°C, while the flux-cored wire deposit toughness was poor.

3) The welding procedure developed for the Hobart Ultra-Arc 350 can be easily transferred to other power supplies with some modification. It is believed that most of the power supplies in the market can be employed for successful P-GMAW.

4) Either CC or CV machines can be used for the P-GMAW process. However, machines which did not have automatic voltage control seemed to perform better for semi-automatic welding.

5) The skills required for P-GMAW can be easily transferred to welders, as demonstrated in the course of this project. However, P-GMAW requires a high level of concentration from the welder, which may not be easily taught.

6) The requirements of a training program are outlined in this report. There is expertise and facilities in Canada to perform the training.

## ACKNOWLEDGEMENTS

This work was initiated within the Metallurgical Research Department of Ontario Hydro Research Division by Mr. M.J. Tinkler. Preliminary stages of the work program were performed by Mr. G.C. Poon. Thanks are due to the staff of the Metallurgy Section in Ontario Hydro Research, for their valuable discussion and, in particular, to Mr. J.G. Galloway for performing some of the welding.

This work was supported through the Metals Technology Laboratories, CANMET, Energy Mines and Resources Canada by the Federal Panel on Energy R & D (PERD). Any data presented, opinions, findings, conclusions or recommendations expressed in this report are those of the authors, and do not necessarily reflect the views of CANMET.

Recommended by:

W.H.S. Lawson
Supervising Engineer
Metallurgy Section
Metallurgical Research Dept

Prepared by:

T.W. Lau
Engineer - Welding
Metallurgy Section
Metallurgical Research Dept

Approved by:

J. Brown
Manager
Metallurgical Research Dept

R. Hopkins
Technician
Metallurgy Section
Metallurgical Research Dept

/iz

## REFERENCES


(1) D.V. Dorling, R.M. Huntley and A.B. Rothwell, "Development Of All-Position Mechanized and Automatic FCAW System for the Fabrication of Offshore Structures and Arctic Vessels", Final report to CANMET, DSS contract OSQ82-00250, July 1984.

(2) D.V. Dorling, R.M. Huntley, J. Geerings and A.B. Rothwell, "Pulsed Gas Metal Arc Welding Of Thick-Section Steels For Low Temperature Applications", Final report to CANMET, DSS contract OSQ84-00042, September, 1986.

(3) C. Chiu and L.Malik, "Toughness Evaluation Of GMA Welding Consumables For Offshore And Petrochemical Applications", Interim report vol.1, MTC-Artec Contract 2517C, March 1987.

(4) G.C. Poon, "Pulsed Gas Metal Arc Welding Development-All Position Manual Pipe Welding", Ontario Hydro Research Division, report no.87-323-K April, 1988.

(5) T.S. Thompson, A.B. Rothwell, and D.V. Dorling, "The Influence Of Shielding Gas Composition on Pulsed Gas Metal Arc Welding Of Arctic and offshore Structures and Pipelines", Final report to CANMET, DSS contract 23440-6-9113/01-SQ, November, 1988.

(6) T.W. Lau, M. Sadowski, T.H. North and G.C. Weatherly, "Nitrogen and Submerged Arc Weld Metal Properties", Materials Science Technology, U.K., 4,52, 1988.

(7) P.R. Kirkwood, Metal Const., May 1978, Pg. 260.

(8) J.G. Garland, and P.R. Kirkwood, Welding and Metal Fab., May 1976, pg. 3.

TABLE 1 - CHEMICAL COMPOSITION OF ELECTRODE WIRES

| Electrode | C | Mn | P | S | Si | Ni | Cr | Mo | Cu | Al | V | Nb | B | Ti | O | N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Thyssen K.NOVA | .06 | 1.40 | .011 | <.005 | .70 | <.01 | .03 | .01 | .08 | .008 | <.005 | <.005 | <.0005 | .033 | .0139 | .0093 |
| Kobe MGS-50LT | .06 | 1.76 | .009 | <.005 | .35 | .02 | .11 | .01 | .30 | <.005 | <.005 | .005 | .0055 | .053 | .0142 | .0020 |
| Nippon YM3 | .05 | 1.72 | .012 | .010 | .40 | .05 | .02 | <.01 | .24 | <.01 | <.01 | N/A | .002 | .05 | .006 | .0029 |
| Nippon | .04 | 1.03 | .014 | .009 | .33 | 2.23 | | | | | | | | | | |

**TABLE 2 - TRA 350 PULSE WIDTH AND BASE CURRENT SETTING VALUES**

| PULSE SETTING | | | CURRENT SETTING | |
|---|---|---|---|---|
| Machine Setting | Pulse width | | Machine Setting | Base current |
| A | 0.2 ms | | a | 20A |
| B | 0.4ms | | b | 30A |
| C | 0.6ms | | c | 40A |
| D | 0.8ms | | d | 50A |
| E | 1.2ms | | e | 60A |
| F | 1.4ms | | | |
| G | 1.4ms | | | |
| H | 1.6ms | | | |
| I | 1.8ms | | | |
| J | 2.0ms | | | |

## TABLE 3

## CURRENT VALUE RANGES FOR OUT-OF POSITION WELDING USING A HOBART ULTRA-ARC 350

| | SOLID WIRE | FLUX-CORED WIRE |
|---|---|---|
| Flat | 90 - 160A | 160 - 200A |
| Vertical - Up | 90 - 130A | 160A |
| 45 Deg Overhead | 90 - 100A | 160A |
| Overhead | 90 - 95A | 160A |

**TABLE 4 - AVERAGE WELD METAL and HAZ CHARPY TOUGHNESS**
**(Tested at -60 Deg. C)**

| SAMPLE | WELD METAL (J)* | HAZ (J)* |
|---|---|---|
| Kobe 160A | 189.7 | 157.3 |
| Kobe 120A | 234.7 | 174.3 |
| Kobe 120A Weave | 123.9 | 98.3 |
| | | |
| Nippon 160A | 211.0 | 204.0 |
| Nippon 120A | 288.3 | 279.4 |
| Nippon 120A Weave | 199.0 | 122.0 |
| | | |
| Flux-Cored 200A | 16.3 | 174 |
| Flux-Cored 160A | 22.3 | 161 |
| Flux-Cored 160A Weave | 31.7 | 140.7 |

* average of 3 readings

**TABLE 5 - NITROGEN and OXYGEN RESULTS**

| SAMPLE NAME | ANALYTE | RESULT | UNITS |
|---|---|---|---|
| Kobe 160A | Oxygen<br>Nitrogen | 302.<br>25. | ppm<br>ppm |
| Kobe 120A | Oxygen<br>Nitrogen | 275.<br>40. | ppm<br>ppm |
| Kobe 120A Weave | Oxygen<br>Nitrogen | 234.<br>51. | ppm<br>ppm |
| Nippon 160A | Oxygen<br>Nitrogen | 240.<br>49. | ppm<br>ppm |
| Nippon 120A | Oxygen<br>Nitrogen | 482.<br>62. | ppm<br>ppm |
| Nippon 120A Weave | Oxygen<br>Nitrogen | 312.<br>68. | ppm<br>ppm |
| Flux-Cored 200A | Oxygen<br>Nitrogen | 377.<br>72. | ppm<br>ppm |
| Flux-Cored 160A | Oxygen<br>Nitrogen | 430.<br>61. | ppm<br>ppm |
| Flux-Cored 160A Weaved | Oxygen<br>Nitrogen | 302.<br>72. | ppm<br>ppm |

## TABLE 6

## SUMMARY OF HARDNESS VALUES OBSERVED IN THE DEPOSITS (UPN 2.5 kg)

| SAMPLE NAME | HARDNESS READING |
|---|---|
| Kobe 160A | 188 |
| Kobe 120A | 218 |
| Kobe 120A Weave | 196 |
| Nippon 160A | 205 |
| Nippon 120A | 210 |
| Nippon 120A Weave | 201 |
| Flux-Cored 200A | 264 |
| Flux-Cored 160A | 273 |
| Flux-Cored 160A Weave | 255 |

## TABLE 7

## SUMMARY OF P-GMA POWER SOURCE CHARACTERISTICS

| | HOBART ULTRA-ARC | FRONIUS TPS 500 | AIRCO PULSEARC 500 | OTC TRA 350 |
|---|---|---|---|---|
| Output Characteristics | cc | cv\cc | cc | cv |
| Primary Control | Invertor | Transistor Chopper | Transistor Chopper | Transistor Chopper |
| Programmability | Fully | Fully | No | Fully |
| Pulse Logic | Synergic $t_b$(frequency) $I_b$ | Synergic $I_p, t_p, I_b, t_b$, wfs | Synergic $t_b$(frequency) | Synergic $t_b$(frequency) |
| Voltage Feedback | WFS on/off | $I_p$(?) | No | Frequency on only |

## TABLE 8

## SUMMARY OF GROOVE WELDMENTS MADE

| POWER SOURCE | HORIZONTAL * | VERTICAL-UP * | 45 Deg OVERHEAD * |
|---|---|---|---|
| Hobart (AVC off) | No Defects | No Defects | No Defects |
| Hobart (AVC on) | Small defects | Small defects | Small defects |
| Airco | No Defects | No Defects | No Defects |
| Fronius | No Defects | No Defects | No Defects |
| TRA 350 | Small defects | Numerous Defects | Numerous Defects |

* (Defects means Lack of Fusion)

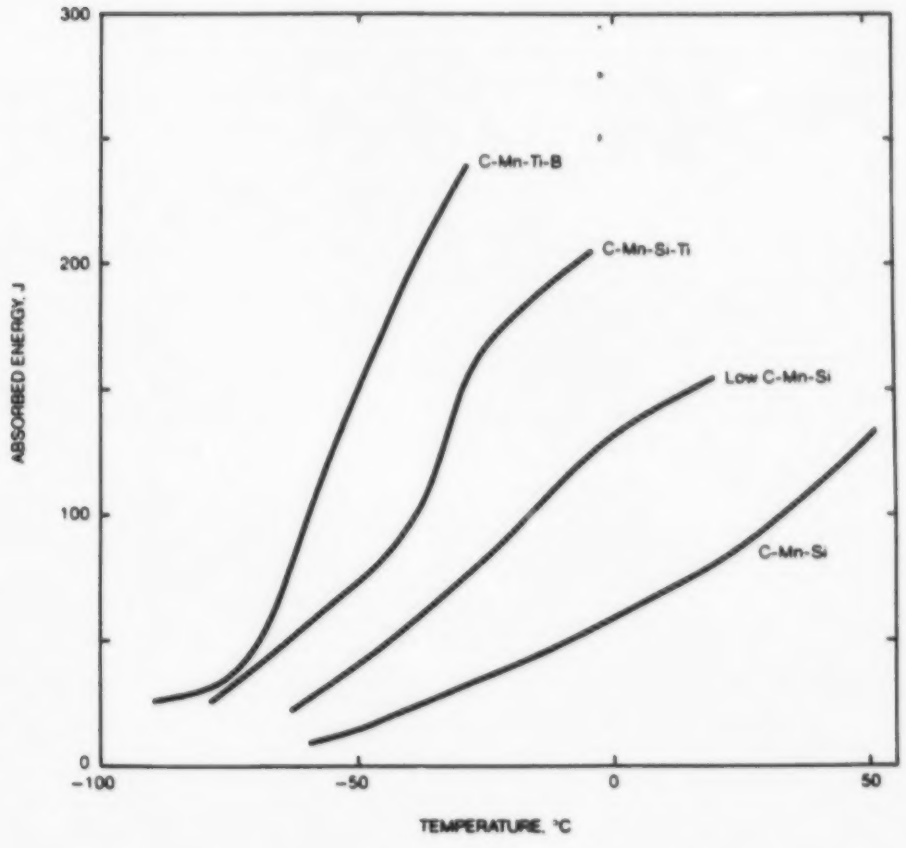


FIGURE 1 - Charpy Impact Transition Curves for C-Mn-Si, LowC-Mn-si, C-Mn-Si-Ti, and C-Mn-Ti-B Welds Made Under 95Ar-5$CO_2$

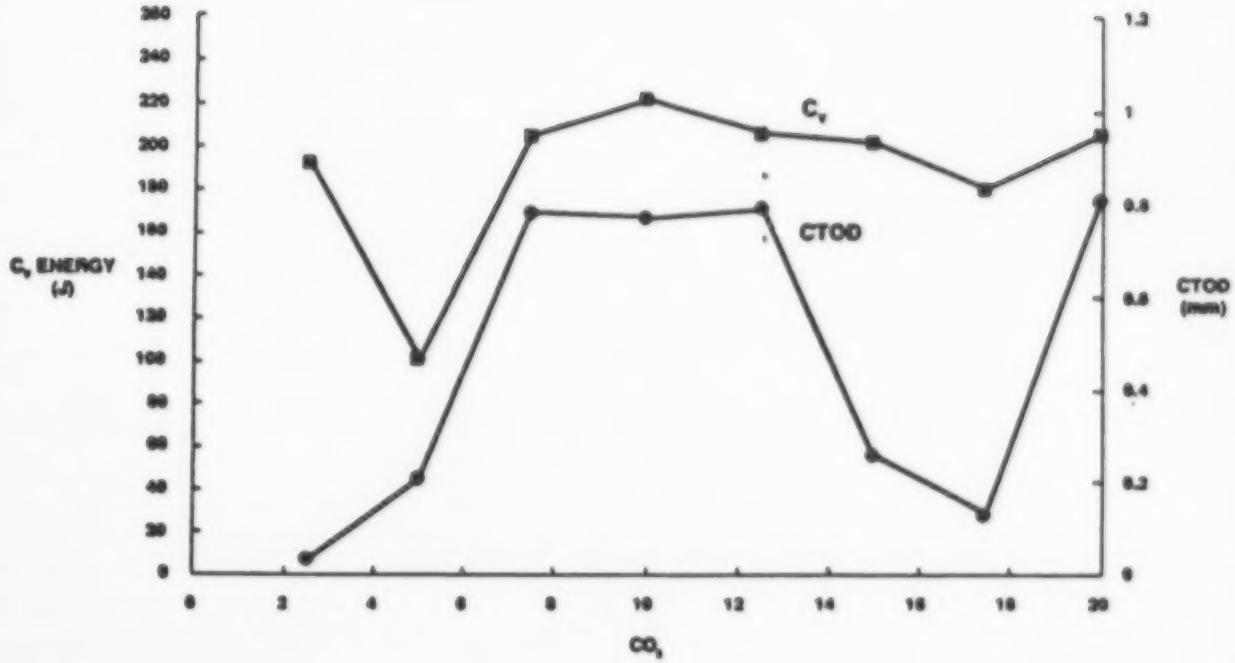


FIGURE 2 - Effect of Increasing Oxidation Potential on C-Mn-Ti-B Weld Metal Toughness Properties

FIGURE 3 - Typical Cross-Section profile of bead on plate welds using 92Ar $8CO_2$ Shielding Gas (5X)

a) Kobe 100A
b) Kobe 170A

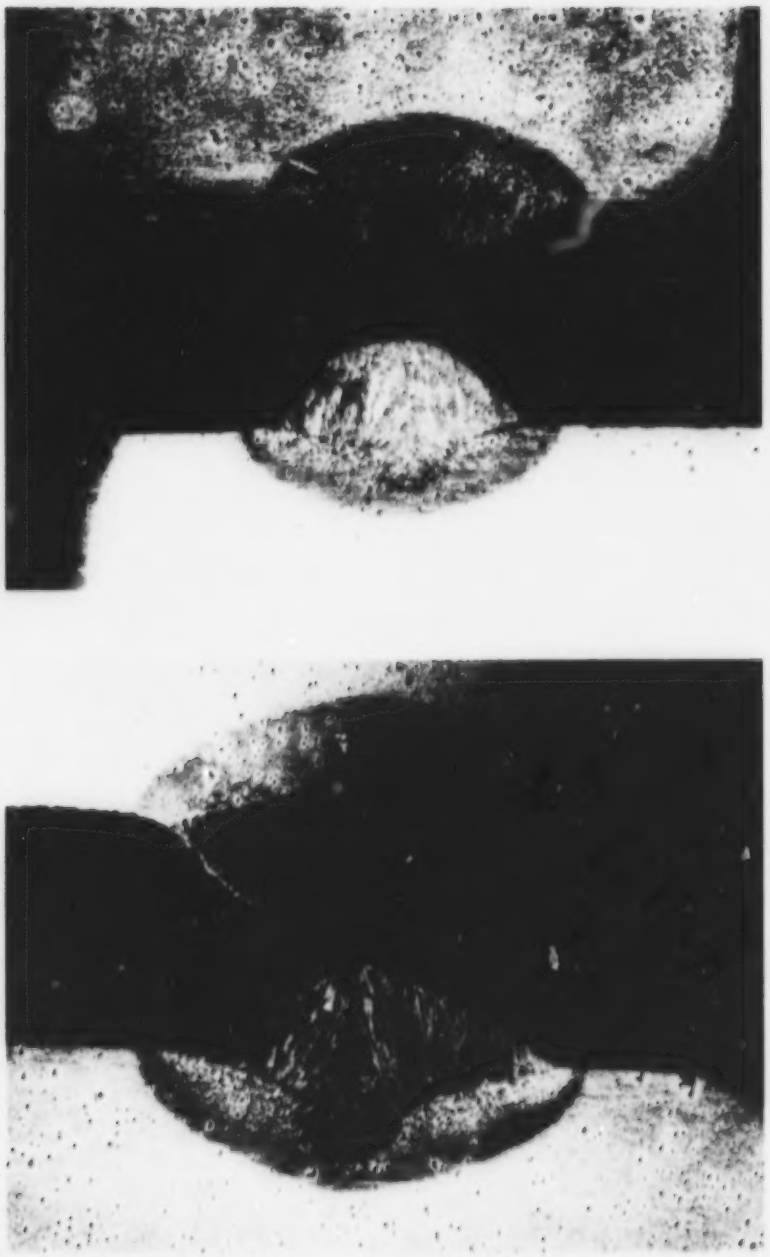

FIGURE 3 - Typical Cross-Section profile of bead on plate welds using 92Ar $8CO_2$ Shielding Gas (5X) (cont'd)

c) Nippon 100A
d) Nippon 170A

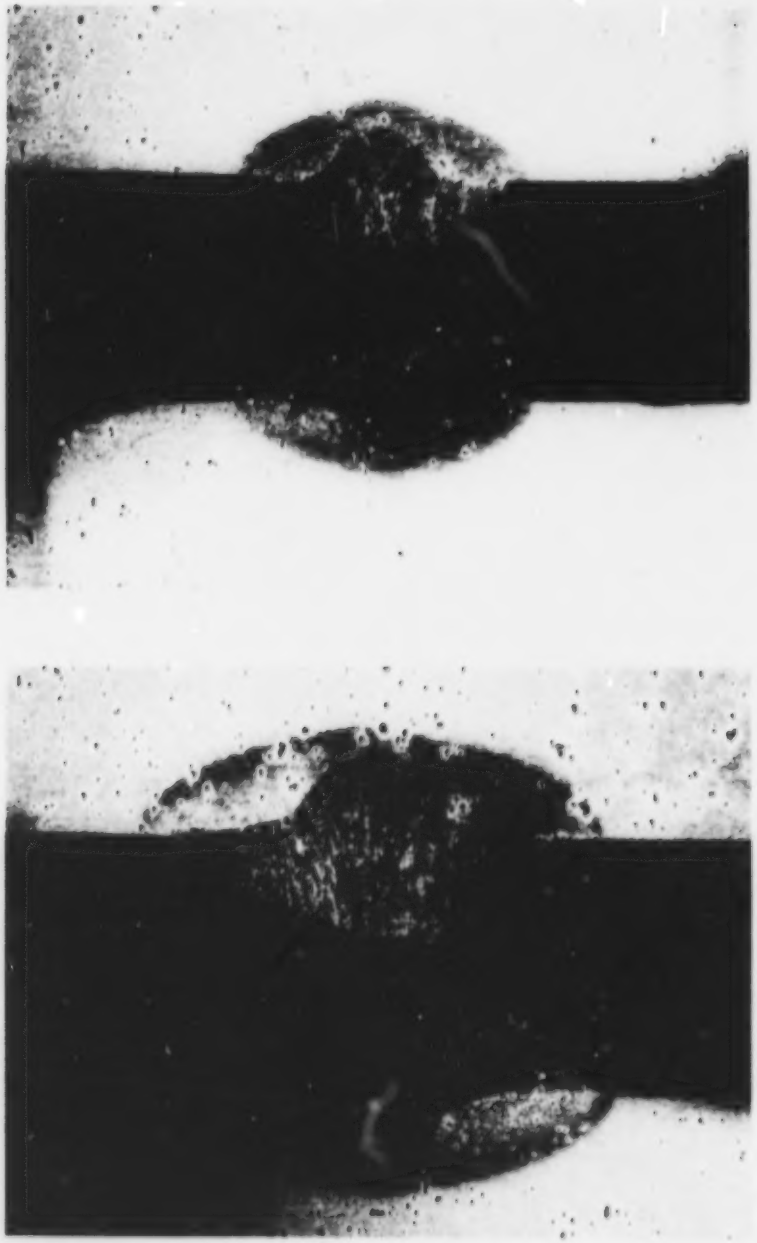

FIGURE 3 - Typical Cross-Section profile of bead on plate welds using 92Ar $8CO_2$ Shielding Gas (5X) (cont'd)

e) Thyssen 0.9mm 100A
f) Thyssen 0.9mm 170A

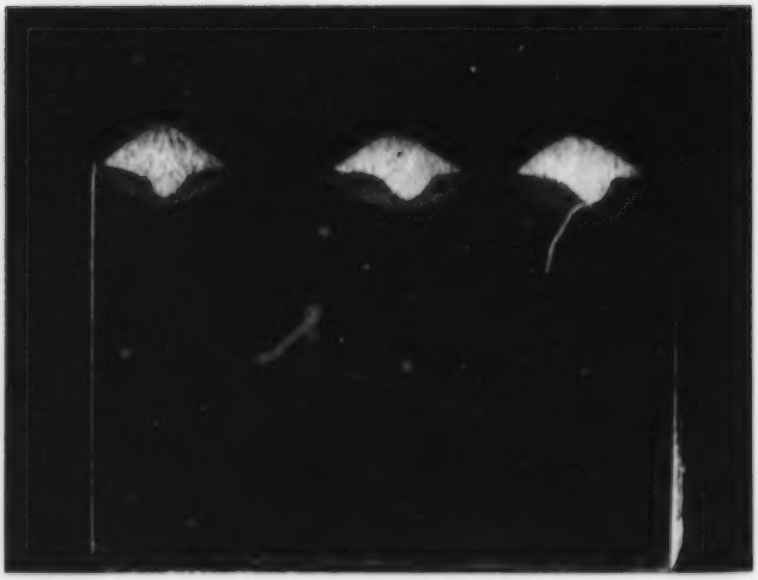

FIGURE 4 - Typical Cross-Section profile of bead on plate weld using Kobe wire, 80Ar 10$CO_2$ Shielding Gas

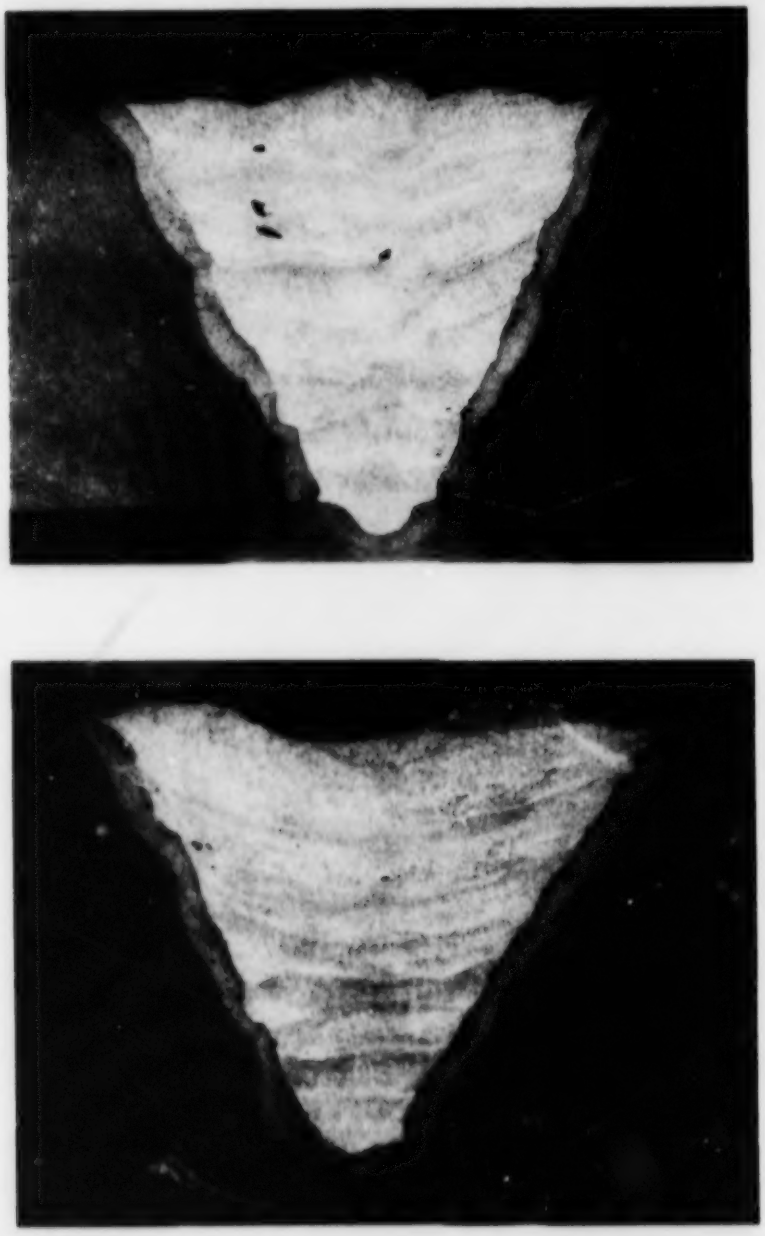

FIGURE 5a - Cross-Section of Groove welds using Kobe wire, 92Ar $8CO_2$ Shielding Gas (2.5X)

(i) Vertical-up split weave
(ii) Vertical full weave

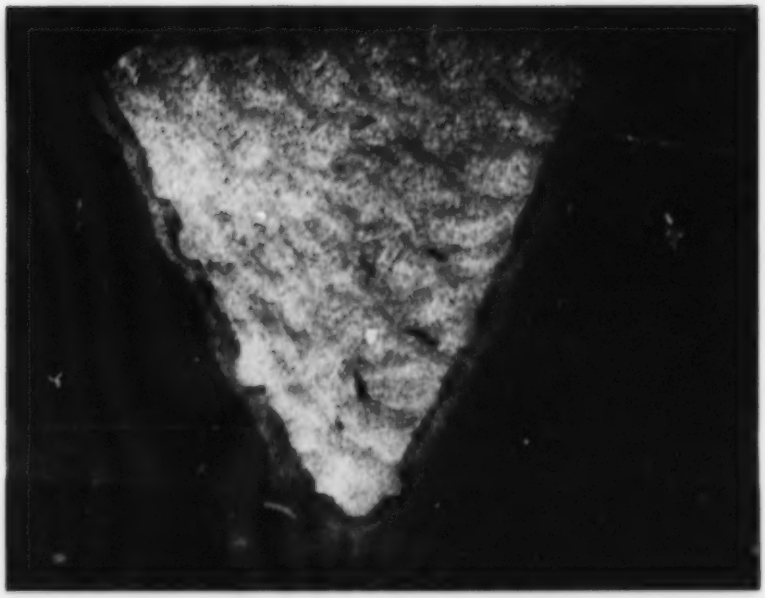

FIGURE 5a - Cross-Section of Groove welds using Kobe wire, 92Ar $8CO_2$ Shielding Gas (5X) (cont'd)

(iii) Horizontal stringer

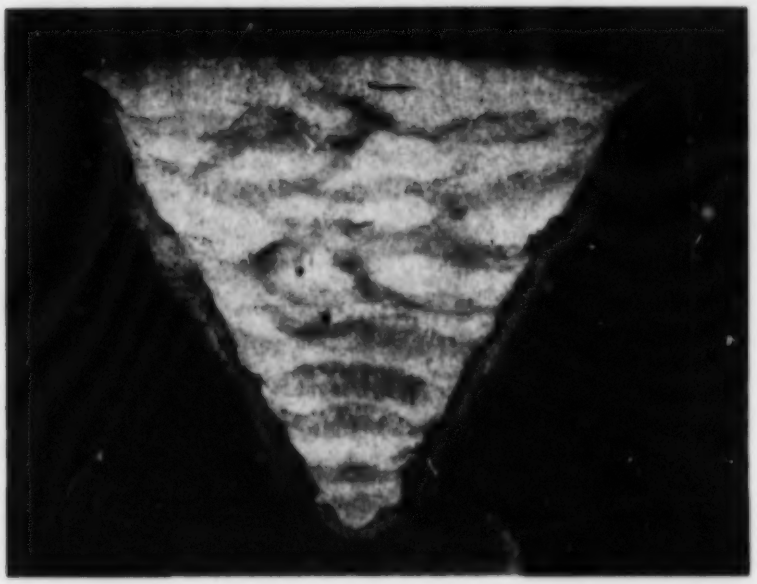

FIGURE 5b - Cross-Section of Groove welds using Nippon wire, 92Ar $8CO_2$ Shielding Gas (2.5X)

(i) Vertical-up split weave
(ii) Vertical full weave

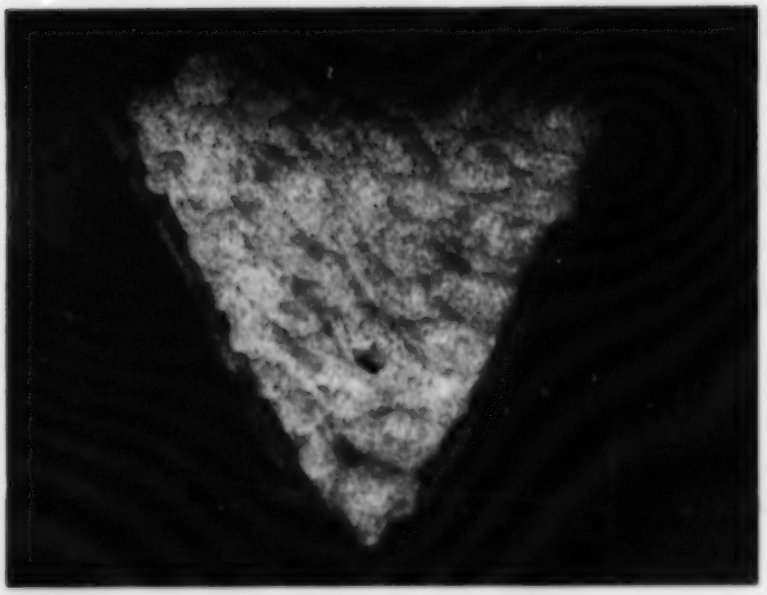

FIGURE 5b - Cross-Section of Groove welds using Nippon wire, 92Ar $8CO_2$ Shielding Gas (2.5X) (cont'd)

(iii) Horizontal stringer

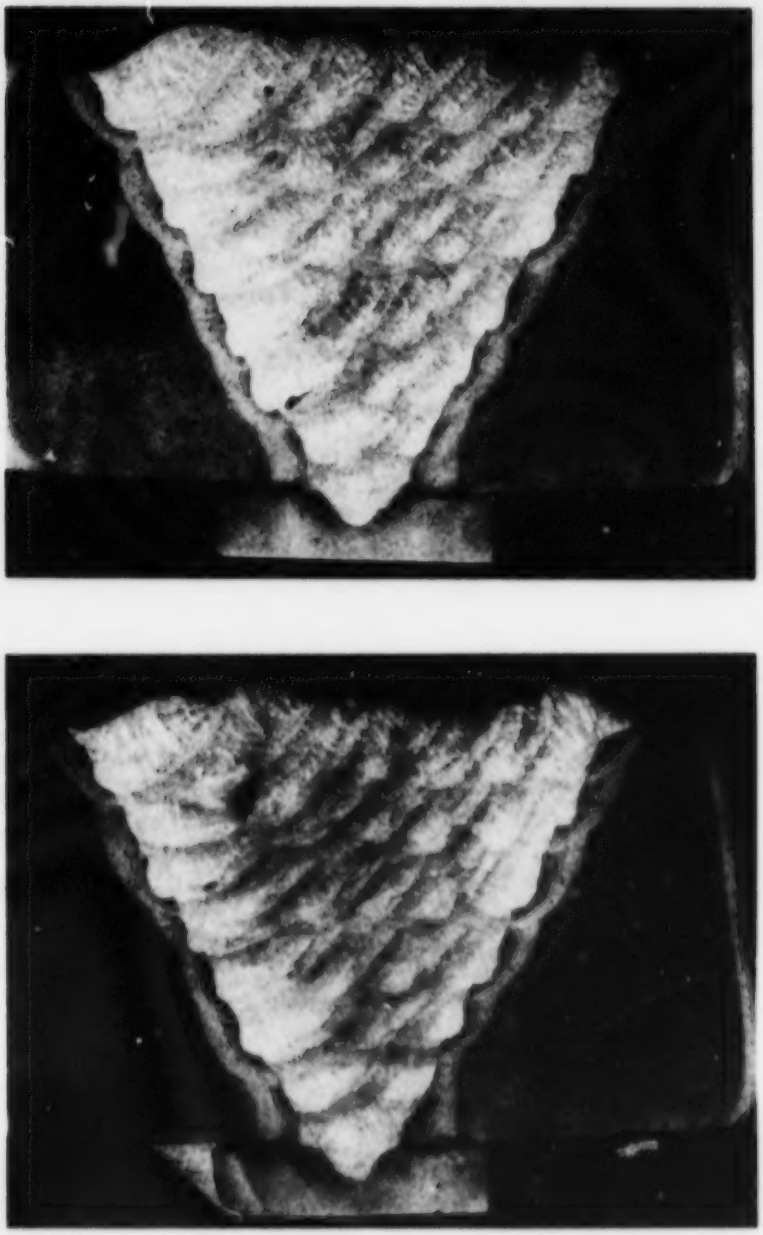

FIGURE 6 - Cross-Section of Groove welds using Kobe wire, 80Ar 10He 10$CO_2$ Shielding Gas (2.5X)

a) Defects were fewer and smaller than when the 92 N 8$CO_2$ Shielding Gas was used

b) Large defect was due to deliberate misplacement of the weld bead

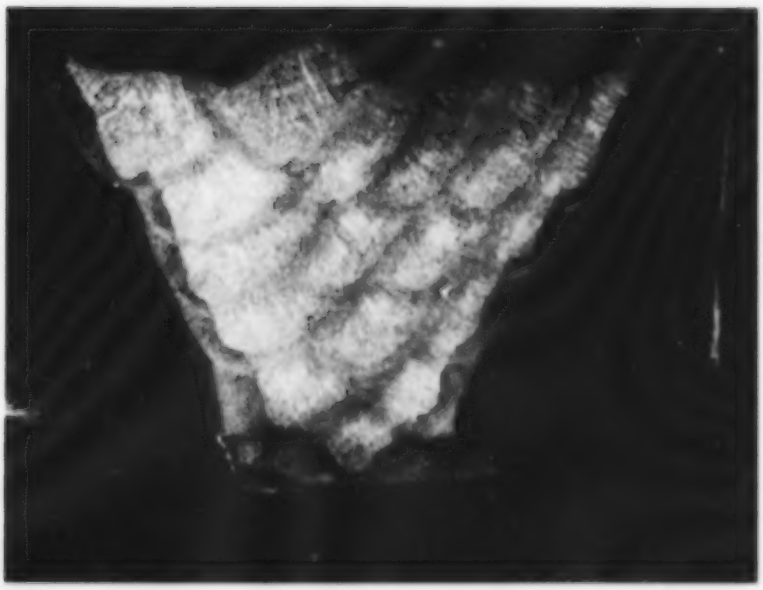

FIGURE 7 - Cross-Section of Groove welds using Nippon wire, 80 Ar 10He $10CO_2$ Shielding Gas at 160A, showing no defects (2.5X)

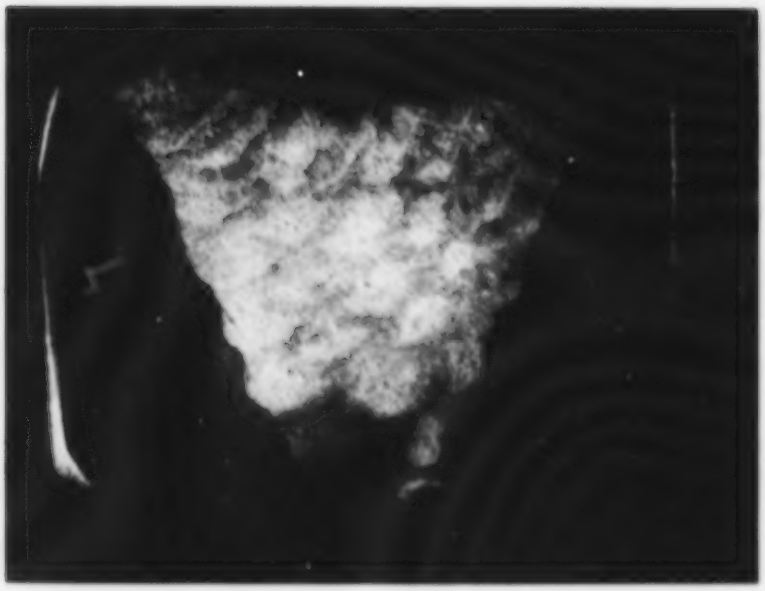

FIGURE 8 - Cross-Section of Groove welds using Hobart AVC off, 92Ar $8CO_2$ Shielding Gas at 110A, in a vertical-up progression (2.5X)

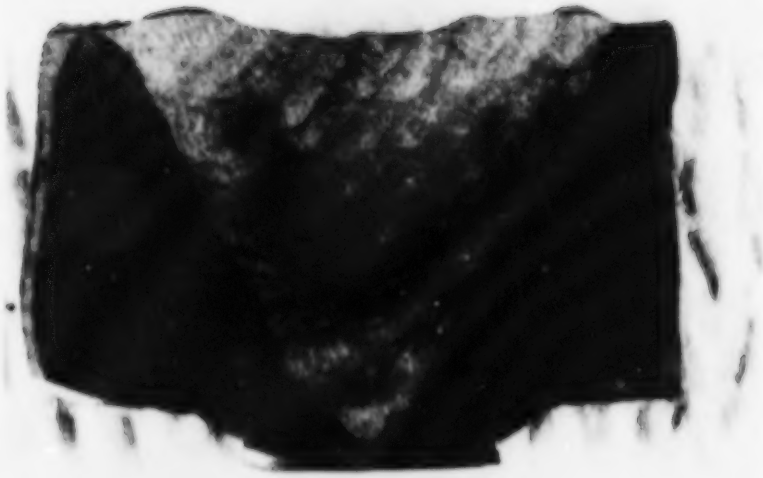

FIGURE 9 - Cross-Section of Groove welds using Hobart AVC on, 92Ar $8CO_2$ Shielding Gas at 110A, in a vertical-up progression (2.5X)

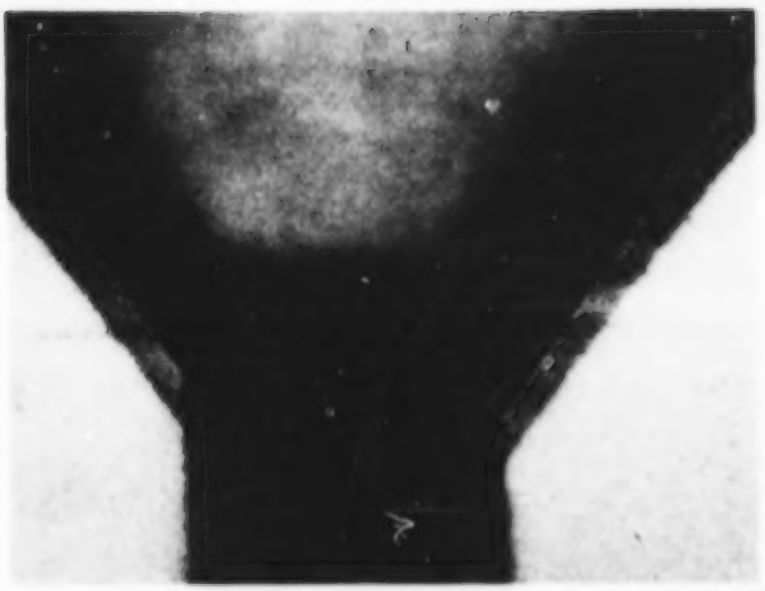

FIGURE 10 - Cross-Section showing bead humping at the root region when welding at low current (~ 90A)

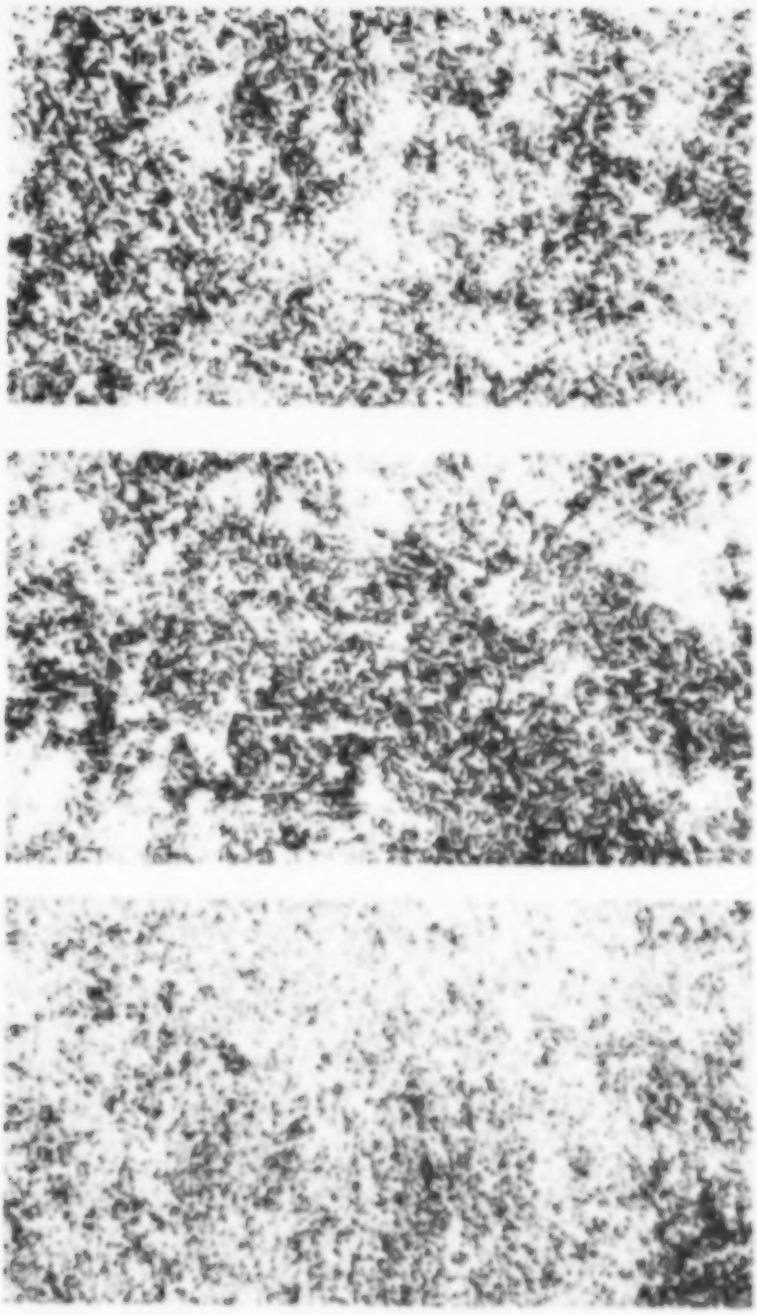

FIGURE 11 - Typical microstructure of weldments made at high current (200 X)

a) Nippon 160A b) Kobe 160A c) Flux Core 200A

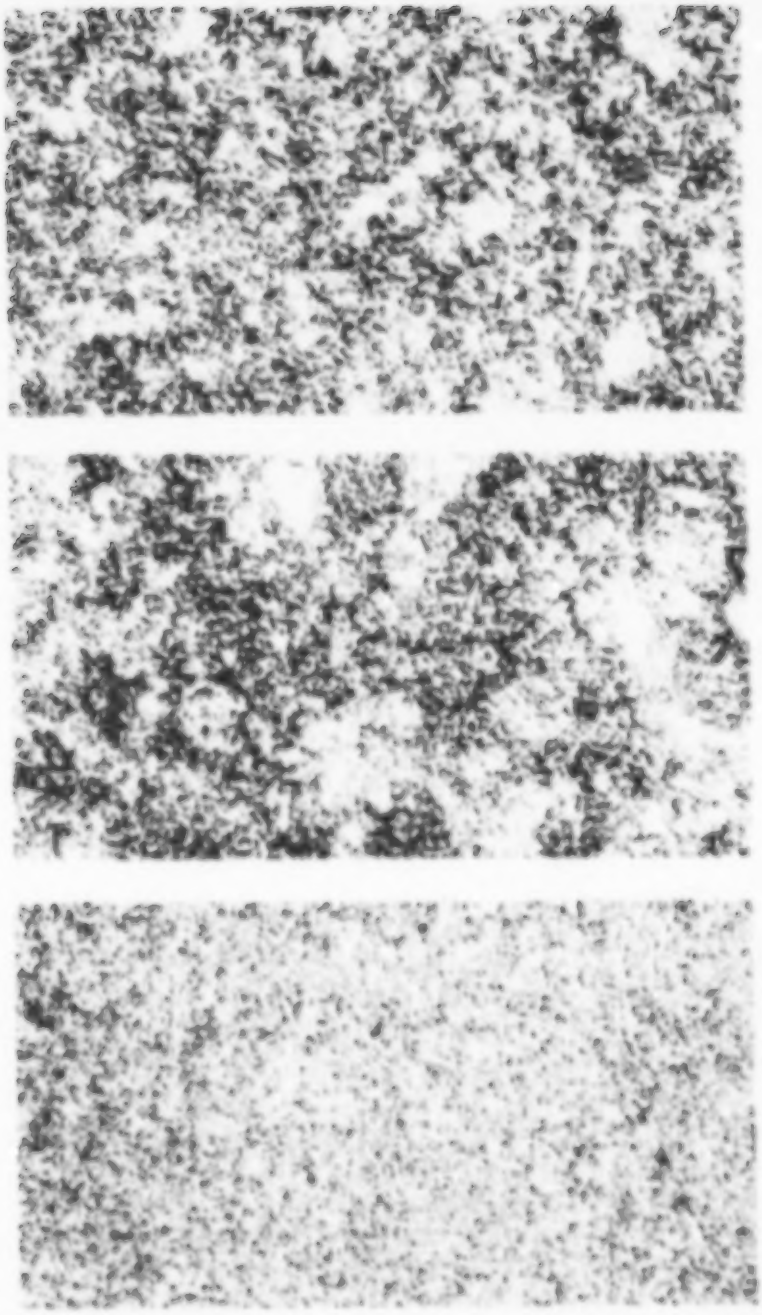

FIGURE 12 - Typical microstructure of weldments made at low current without weaving (200 X)

a) Nippon 120A b) Kobe 120A c) Flux Core 160A

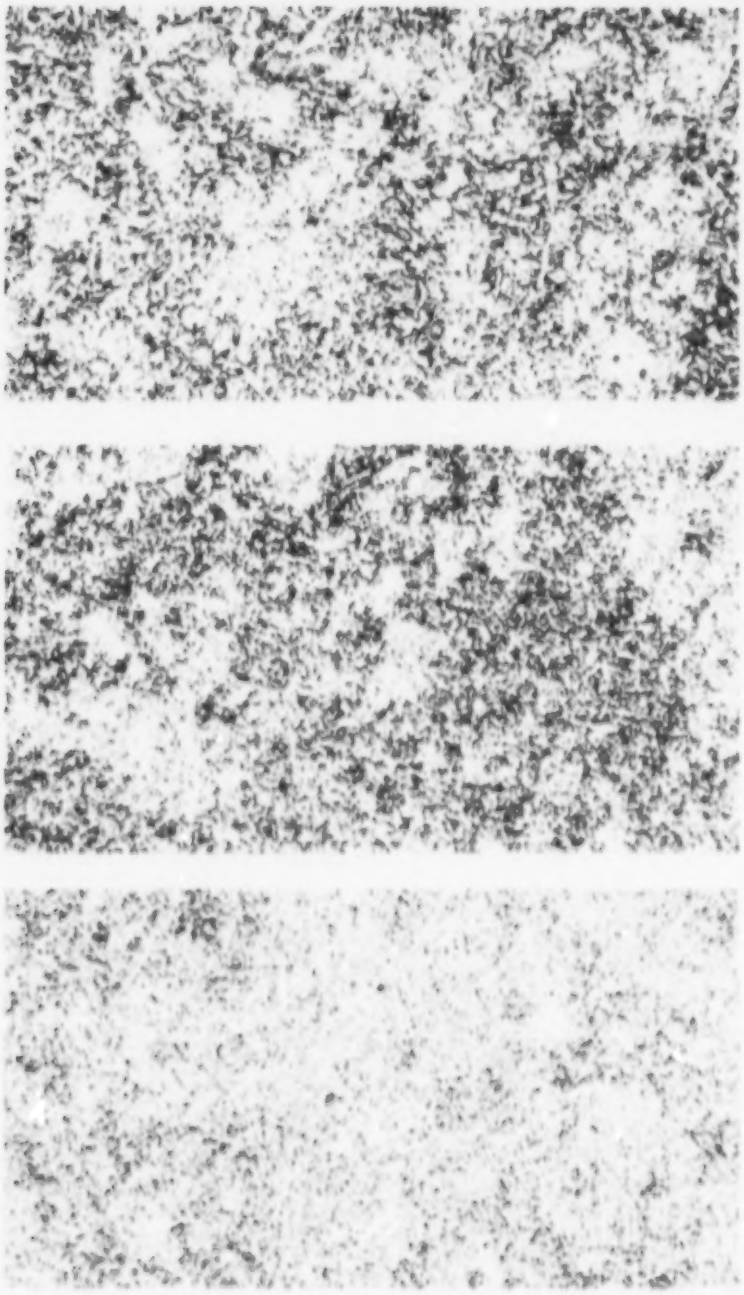

FIGURE 13 - Typical microstructure of weldments made at low current with weaving (200 X)

a) Nippon 120A b) Kobe 120A c) Flux Core 160A

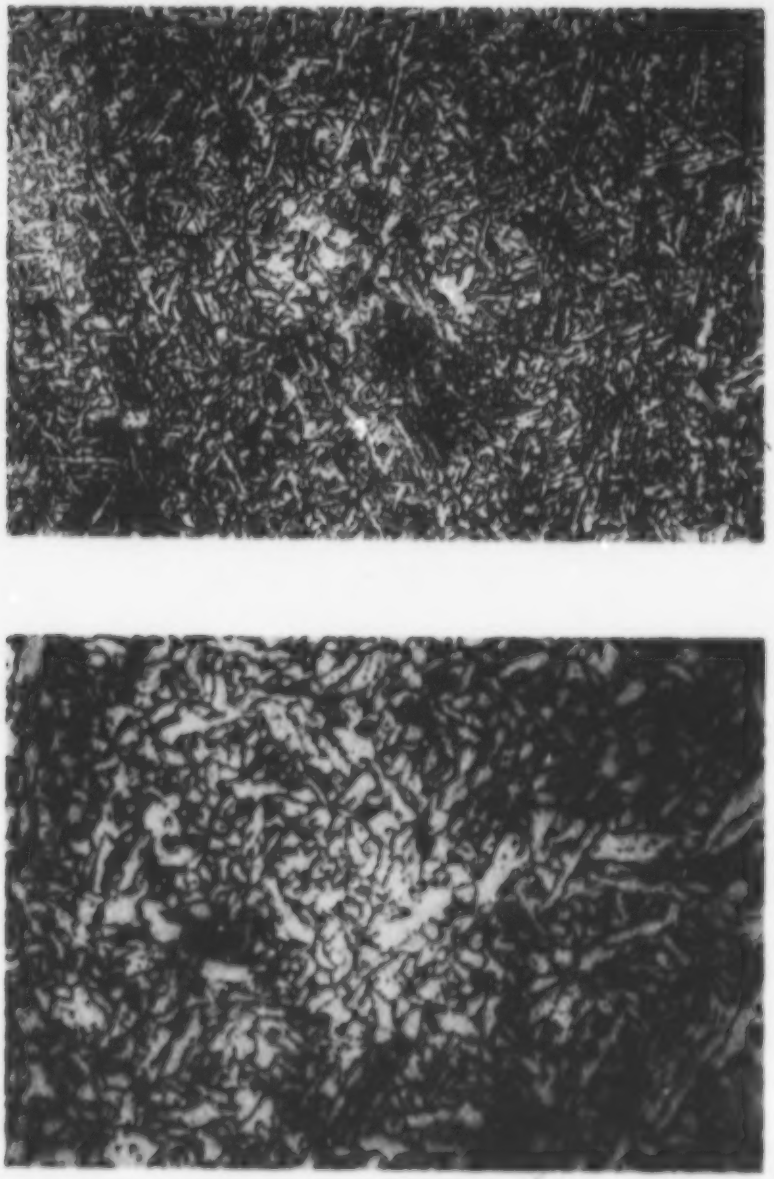

FIGURE 14 - Typical microstructure of Kobe deposits

a) X500 b) X1000

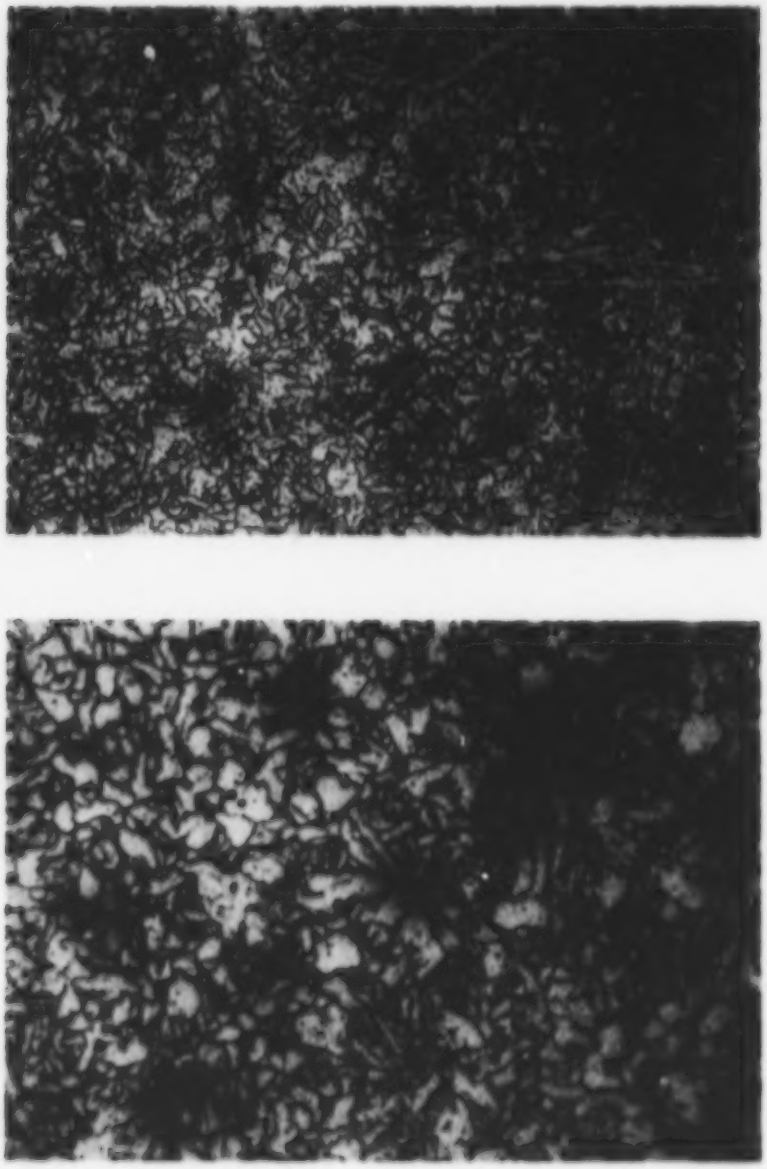

FIGURE 15 - Typical microstructure of Nippon deposits

a) X500 b)X1000

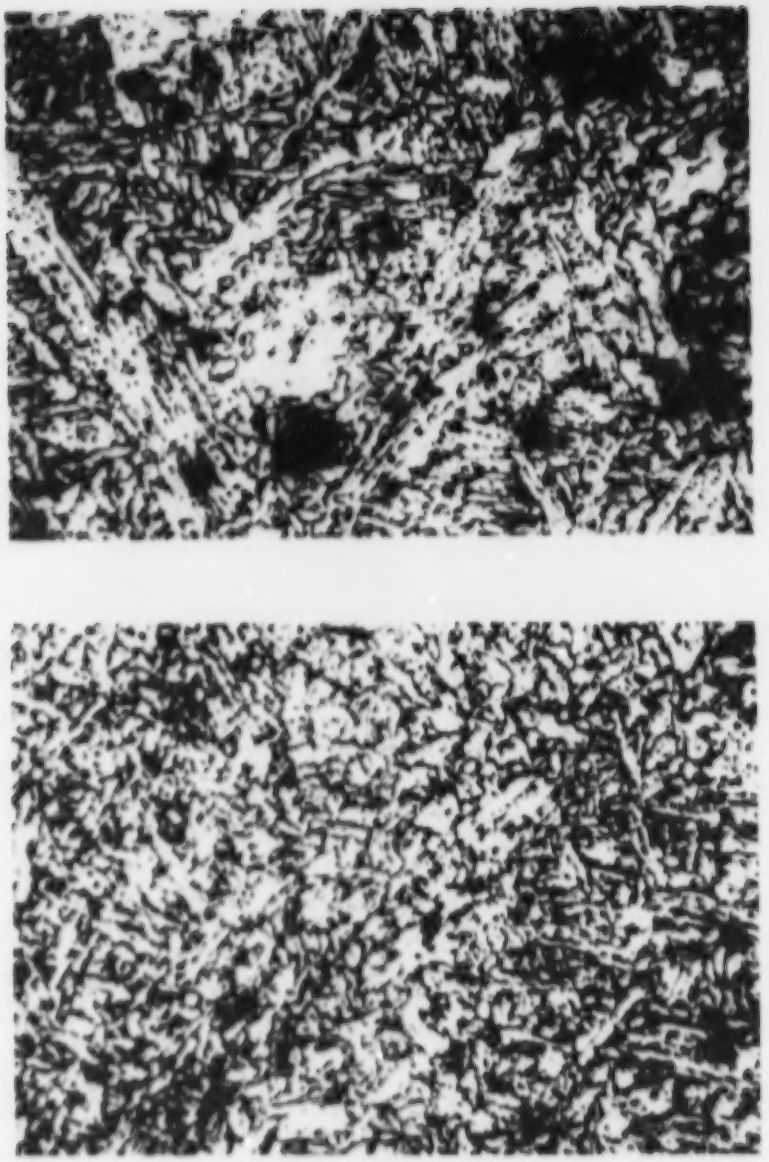

FIGURE 16 - Typical microstructure of flux-cored wire deposits

a) Coarse grained area X1000
b) Fine acicular ferrite area X1000

FIGURE 17 - Longitudinal cross-section from an all position pipe weldment

**DISTRIBUTION**

| | |
|---|---|
| Dr. J.M.E. Braid (10) | CANMET |
| Mr. R.W. Patterson | CPS, A8-H6 |
| Dr. D. Sidey | CPS, A8-H6 |
| Mr. J.W. Prince | CPS, A8-G4 |
| Mr. G.C. Poon | CPS, A8-H5 |
| Mr. J.T. Martin | D&D-Gen, H14-A21 |
| Mr. L.F. Robertson | Bruce CMF |
| Dr. J. Brown | Metallurgical Research |
| Dr. W.H.S. Lawson | Metallurgical Research |
| Mr. M.J. Tinkler | Metallurgical Research |
| Dr. M.A. Clark | Metallurgical Research |
| Dr. H.J. Westwood | Metallurgical Research |
| Mr. P.Y.Y. Maak | Metallurgical Research |
| Mr. J.G. Galloway | Metallurgical Research |
| Mr. E.M. Mathers | Metallurgical Research |
| Mr. R.W. Hopkins | Metallurgical Research |
| Dr. T.W. Lau | Metallurgical Research |
| Mr. D. Hartwick | Metallurgical Research |

APPENDIX A

## P-GMA OPERATOR TRAINING PROGRAM(DURATION 2 WEEKS

R.W. Hopkins

The purpose of the training period is to familiarize an operator with the Pulsed Gas Metal Arc (P-GMA) welding process. This program should develop a sufficient level of skill to enable this operator to manually weld plate and pipe in all positions and to code requirements, if warranted.

The program should be tentatively scheduled as follows:

Day 1: Theory of the P-GMA process, its operating peculiarities and where the operator has previous GMA welding experience, the differences between pulsed and non-pulsing systems should be covered.

Hands-on familiarization with the equipment.

Bead-on-plate exercises with varying power settings and travel speeds to develop the technique required to produce acceptable bead width, contour, wetting etc.

Day 2: Development of techniques of correct bead spacing, wash-up and multilayer welding in the flat position.

Repeat of above in the horizontal position.

Day 3: Repeat of above in overhead position.

Vertical-up beads. Since vertical-up has proven to be the least forgiving of all positions of P-GMA welding the operator needs to develop the low power weave technique necessitated by the process limitations.

Day 4: Assuming the foregoing exercises are successful, it should be possible to produce a multipass groove weld in plate on the fourth day. To further concentrate the training period, it is felt that this test plate should be welded in the horizontal mode rather than in the flat (downhand).

Day 5: While assessment (NDE, metallography, etc) of the day 4 plate is being performed, the operator should shift his efforts to the welding of pipe utilizing the knowledge gained from the previous four days.

Days 6 to 10: An attempt should be made at this time to produce a representative, though not necessarily a formal, pipe sample, welded in the 5G position. Evaluation of this sample coupled with the foregoing work should indicate the feasibility of producing a formal (as per MCCR requirements) test coupon.

***Kawneer***
***CTL Program Outline***
***GMAW Training***

1.0 Course Outline (6 hours per day)

Day 1 - Welding Health and Safety
Day 2 - GMAW, Theory and Practical
Day 3 - GMAW, Theory and Practical
Day 4 - GMAW, Practical
Day 5 - GMAW, Practical

2.0 Course Content - Classroom (Theory)

GMAW Welding

- Fundamentals
- Metal transfer
- Transition currents
- Shielding gases
- The GMAW wire feeding system
- Effects of parameters
    - WFS, voltage, polarity
    - Stick-out
    - Gun angle
    - Wire diameter
    - Welding speed
- GMAW defects and how to avoid them
- Weld repairs

3.0 Costs

Included are:

- Preparation of course material
- Presentation by a professional engineer
- Practical training by a qualified instructor
- A course manual for each participant as part of the CTL program
- Development of exercises
- Audio-visual aids
- A WIC diploma for each participant